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EFFECT OF ENCLOSURE SHAPE ON NATURAL CONVECTION VELOCITIES

SEPTEMBER 1982

Contract NASW-3281

TECHNICAL REPORT

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by

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FOREWORD

This technical report documents the results of effort by personnel of Lockheed Missiles & Space Company, Inc., Huntsville Research & Engineering Center, for the National Aeronautics and Space Administration in partial fulfillment of Contract NASW-3281. "Manufacturing in Space: Fluid Dynamics Numerical Analysis." The NASA Technical Director is Dr. Robert F. Dressler, Manager, Advanced Technology Program, NASA Headquarters, Washington, D.C.

ABSTRACT

A numerical analysis was performed to compare natural convection velocities in two-dimensional enclosures of various shape. The following shapes were investigated: circle, square, horizontal and upright 2 x 1 aspect ratio rectangles, horizontal and upright half-circles, diamond (square oriented with diagonal vertical) and triangle (equilateral with horizontal base). In all cases, the length scale in the various dimensionless parameters, such as Rayleigh number, is defined as the diameter of the equal area circle. Natural convection velocities were calculated for Rayleigh numbers of 1000 and 5000 with the temperature difference taken to be across (a) the maximum horizontal dimension, (b) the median horizontal line (line through centroid) and (c) the horizontal distance such that the temperature gradient is the same for shapes of equal area. A Rayleigh number of 1000 is within the "low Rayleigh number" range for agreement with first order theory for circular enclosures. A Rayleigh number of 5000 is slightly out of this range. For the class of shapes including the square, upright half-circle and upright rectangle, the computed velocities were found to agree very closely with that of the equal area circle when the temperature difference is taken to be across the maximum horizontal dimension (condition (a)). The velocities for the horizontal rectangle and half circle were found to be approximately one-half that of the equal area circle for the same condition. Better overall agreement among all shapes was obtained by setting the temperature difference across a distance such that the temperature gradients were equal for shapes of equal area.

ACKNOWLEDGMENT

The investigation described in this document was suggested by Dr. Robert F. Dressler, the NASA Technical Director of this program. We gratefully acknowledge his guidance and support of our efforts throughout this investigation. We also wish to acknowledge the contributions of Lawrence W. Spradley to this program. His overall knowledge of the field of computational fluid dynamics in general, and natural convection in particular were made available throughout the program through enlightening technical discussions.

CONTENTS

NOMENCLATURE

Symbol	Description
d	equal area circle diameter
g	gravity force
R	circle radius
Ra	Rayleigh number = $\frac{g\beta\Delta Td^3}{\nu\alpha}$
ΔT	temperature difference
t	time
v	velocity
α	thermal diffusivity
β	volumetric coefficient of thermal expansion
μ	dynamic viscosity
ν	kinematic viscosity, μ/ρ
ψ	stream function
ρ	density

1. INTRODUCTION

A number of fluid mechanics experiments are to be performed aboard orbiting spacecraft, primarily to investigate the possible use of the near-zero gravity environment in various materials processing applications. A knowledge of the intensity of convective stirring due to residual accelerations is required in order to properly plan and evaluate the experiments. Various shaped containers will be used in these experiments. Theoretical results have been obtained which yield exact predictions of natural convection velocities in an idealized container, i.e., the two-dimensional circular enclosure (Ref. 1). It would be helpful for estimation purposes if a reasonable means existed for the extrapolation of the circular enclosure results to more complex shapes. A previous study demonstrated extremely good agreement in computed natural convection velocities for circular and square enclosures of equal cross-sectional area (Ref. 2). Dressler (Ref. 3) made use of this noted agreement in circular and square enclosure results, in addition to the more general results documented herein, to analyze natural convection in the proposed Lal, Kroes and Wilcox crystal growth experiment to be performed infight on Spacelab 3. The purpose of this investigation is to develop reasonable extrapolation criteria by comparing numerically computed natural convection velocities for various two-dimensional enclosure shapes with the circular enclosure results. The Lockheed-developed General Interpolant Method (GIM) computer code (Ref. 4) was used in the numerical computations.

2. METHOD OF APPROACH AND NUMERICAL SIMULATION

The following set of two-dimensional enclosure shapes was considered: circle, square, 2 x 1 aspect ratio rectangle in both upright and horizontal orientations, half-circle in both upright and horizontal orientations, diamond (square oriented with diagonal vertical) and triangle (equilateral with horizontal base). The baseline condition was selected for equal area with the temperature difference set across the maximum horizontal dimension. The initial temperature distribution was based on a uniform horizontal gradient with the boundary points held constant in time. The gravity vector was considered to be constant in the downward direction. The fluid was assumed to behave as a boussinesq fluid in its thermal expansion characteristics.

The numerical simulation was based on dividing the various enclosures into a computational grid consisting of a network of generalized quadrilateral elements with curvilinear sides, with the nodal points located at the four corners of each element. Each of the enclosures considered in this study was treated as a generalized quadrilateral region divided by interpolation into an array of 20 x 20 elements. For example, the circle was treated as a four-sided figure, each side being a quarter-circle arc.

The triangle was treated by forming a parallelogram such that two adjacent sides and the diagonal formed the desired triangle. The entire parallelogram was divided into a computational grid, but the diagonal points were treated as boundary points. The parallelogram with the diagonal boundary thus formed two independent triangular regions. The computational grids for the enclosures considered in this study are shown in Figs. 1 - 5.

The grids for the square and diamond are the same since the diamond is simply a square with the diagonal in the upright position. The rectangle and half-circle grids are identical in either the upright or horizontal positions.

3. RESULTS

The velocity histories for the various shaped enclosures are shown in Figs. 6 and 7 for Rayleigh numbers of 1000 and 5000. The various enclosures are all of equal area, with the dimensionless velocities and Rayleigh numbers defined based on a temperature difference ΔT across the maximum horizontal dimension, and a length scale equal to the diameter d of the equal area circle. Note that, for a Rayleigh number of 1000 the steady state velocities of the equal area circle and square are very close to identical, with the upright rectangle and half-circle being within about 5% of the circle value. The horizontal rectangle and half-circle, and the triangle steady state velocities form another grouping of values approximately one-half the circle value. The diamond results appear approximately midway between the two extremes. Roughly the same trend of steady state values appear for a Rayleigh number of 5000. Overall, the steady state velocities for the various equal area enclosures are in agreement within a factor of approximately 2.

Response times for the various enclosure results are shown in Fig. 8 for both 1000 and 5000 Rayleigh number. Agreement within a factor of approximately 2 is shown for all enclosures. These response times are defined as the time required to reach the fraction 1 - 1/e (0.632) of the maximum or steady state velocities, whichever is greater, in Figs. 6 and 7.

An attempt was made to find other bases for correlating the data to yield better agreement between the results for the various shaped enclosures. Including the base line correlation, described earlier, correlations were made for the following sets of conditions concerning the distance over which the temperature difference was taken:

- Temperature difference across maximum horizontal dimension (base line correlation).

- o Temperature difference across median horizontal line (line through centroid). Only the triangle and horizontal half-circle results changed in this correlation from the baseline correlation.

- o Temperature difference taken across a distance such that the temperature gradient is the same for all shapes.

The steady state results for the above sets of correlations are summarized in Fig. 9 for a Rayleigh number of 1000, and in Fig. 10 for a Rayleigh number of 5000. For each of the correlation sets, the length scale in the Rayleigh number and dimensionless velocity is taken to be the diameter of the equal area circle. A comparison of the three correlation sets shows improved correlation for the triangle and horizontal half-circle by taking the temperature difference across the median horizontal line rather than the maximum horizontal dimension. Generally better correlation is obtained by setting the temperature gradients equal. This is equivalent to taking the temperature difference across a distance equal to the diameter of the equal area circle.

Computer generated streamline, absolute velocity and temperature contour plots for all of the enclosures are shown in Figs. 11 through 34 at steady state for both 1000 and 5000 Rayleigh numbers.

4. CONCLUSIONS

Natural convection velocities within two-dimensional enclosures of various shape, for Rayleigh numbers up to at least 5000, may be estimated with reasonable accuracy by considering the area to be equivalent to a circle of equal area. For the class of figures including the square, upright half-circle, and upright 2 x 1 aspect ratio rectangle, excellent agreement is obtained by considering the temperature difference across the maximum horizontal dimension to be equal to that across the equal area circle horizontal diameter. The agreement of the two upright oblong shapes indicates probable agreement for any similar upright oblong shape of roughly the same aspect ratio.

The horizontal oblong shapes have natural convection velocities approximately one-half that estimated based on the equal area circle with the temperature difference across the maximum horizontal dimension taken to be equal to that across the equal area circle diameter. As with the upright shapes, this probably indicates a general pattern for similar oblong shapes of roughly the same aspect ratio.

Better overall agreement among all shapes is obtained by setting the temperature difference across a distance equal to the diameter of the equal area circle, thus making the temperature gradients equal for any shape.

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2. Robertson, S.J., L.W. Spradley and M.P. Goldstein, "Numerical Analysis of Natural Convection in Two-Dimensional Square and Circular Containers in Low Gravity," LMSC-HREC TR D697821, Lockheed Missiles & Space Company, Inc., Huntsville, Ala., August 1980.

3. Dressler, Robert F., "Approximate Analysis of Thermal Convection in a Crystal-Growth cell for Spacelab 3," NASA Technical Paper 2026, June 1982.

4. Spradley, L.W., and M.L. Pearson, "GIM Code User's Manual for the STAR-100 Computer," NASA Contractor Report 3157, November 1979.

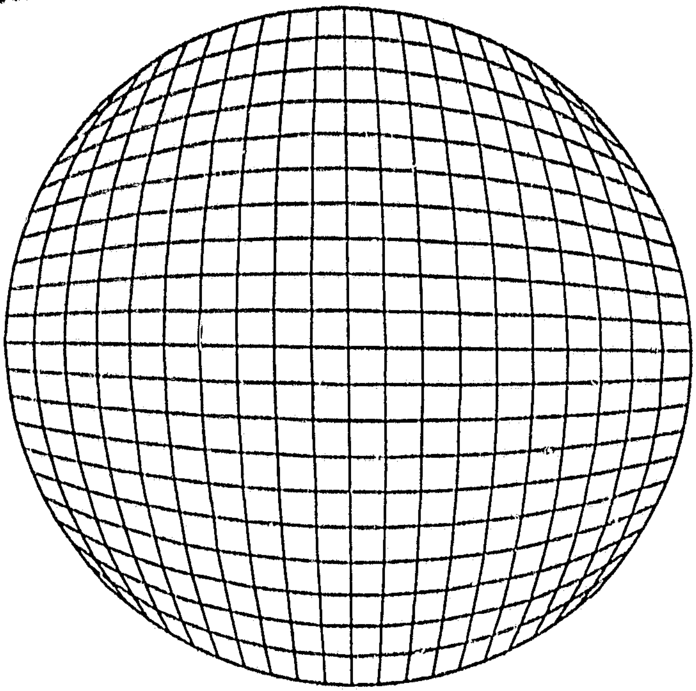

Fig. 1 - Computational Grid: Circle

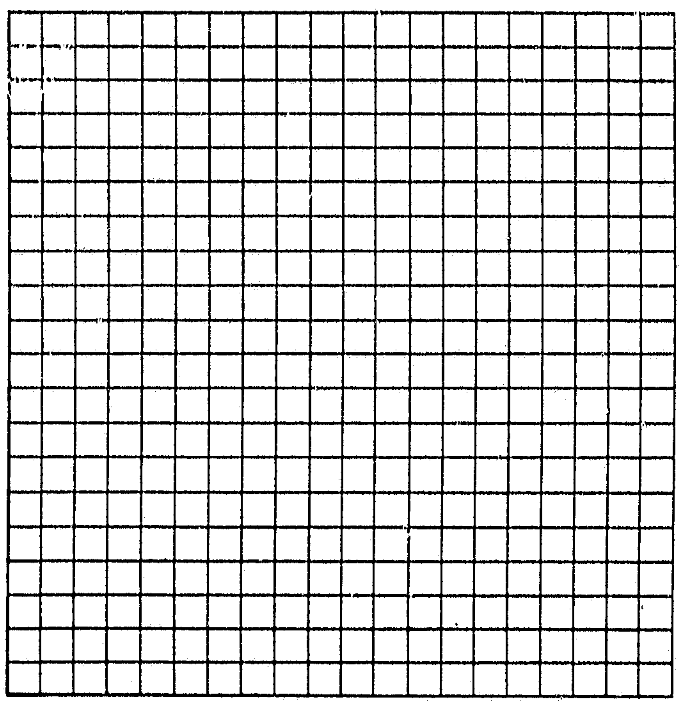

Fig. 2 - Computational Grid: Square and Diamond

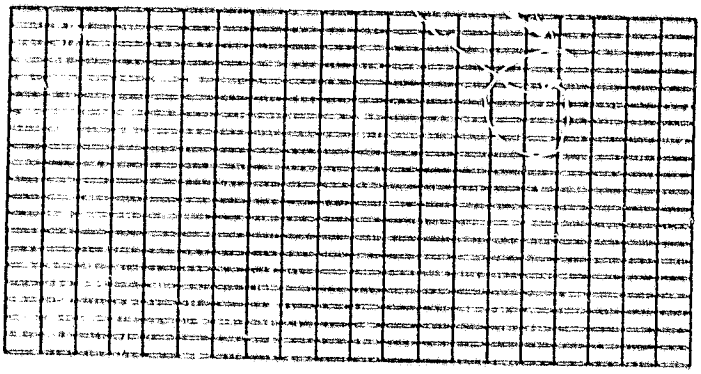

Fig. 3 - Computational Grid: 2x1 Aspect Ratio Rectangle

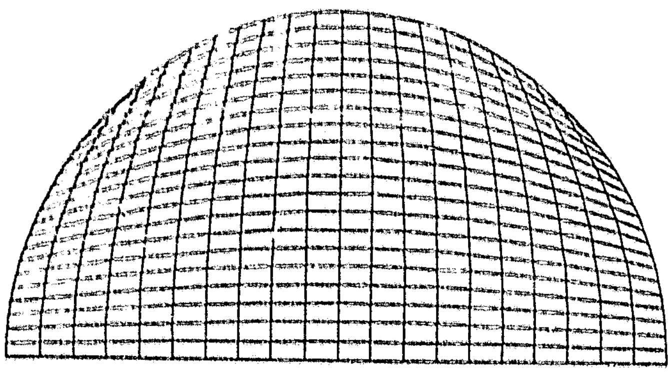

Fig. 4 - Computational Grid: Half-Circle

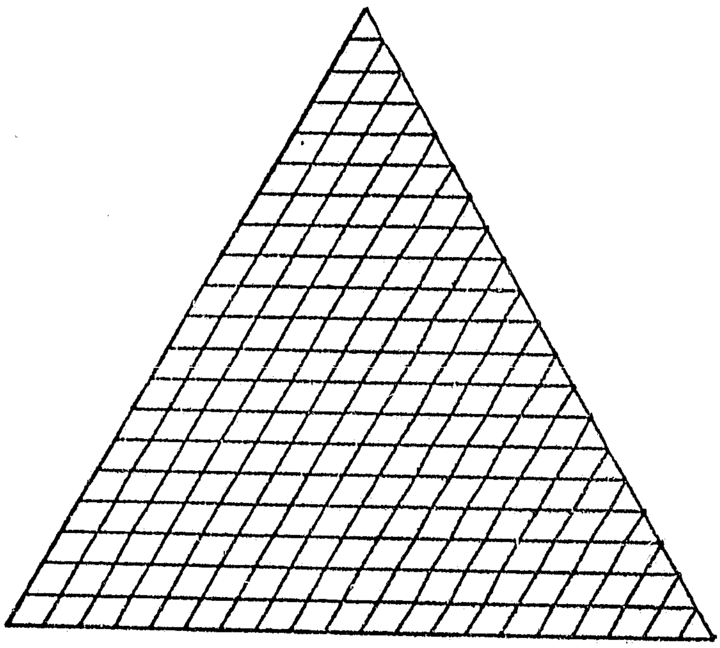

Fig. 5 - Computational Grid: Triangle

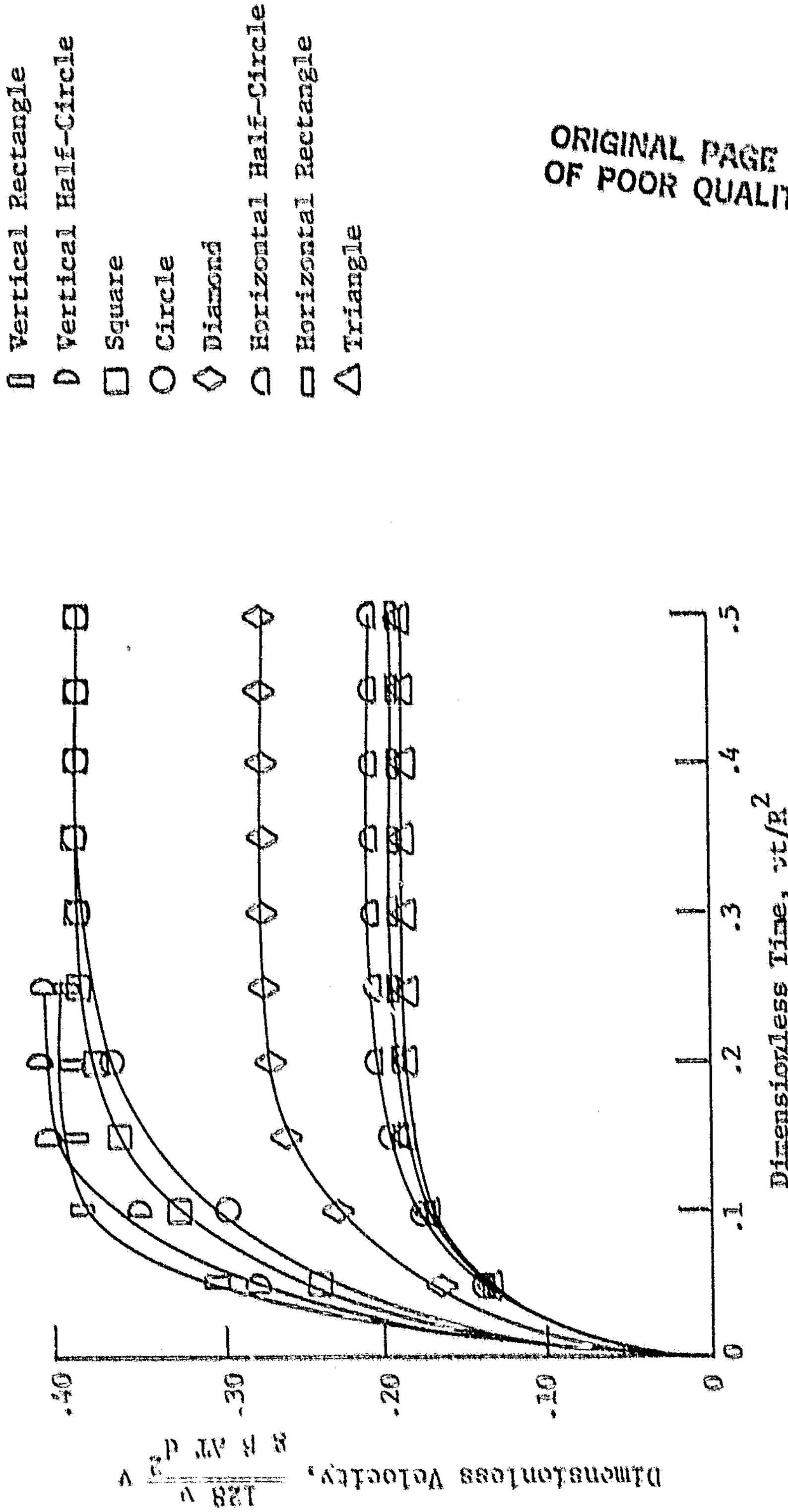

Fig. 6 – Velocity Histories for Natural Convection in Two-Dimensional Enclosures of Various Shape and Raleigh Number of 1000

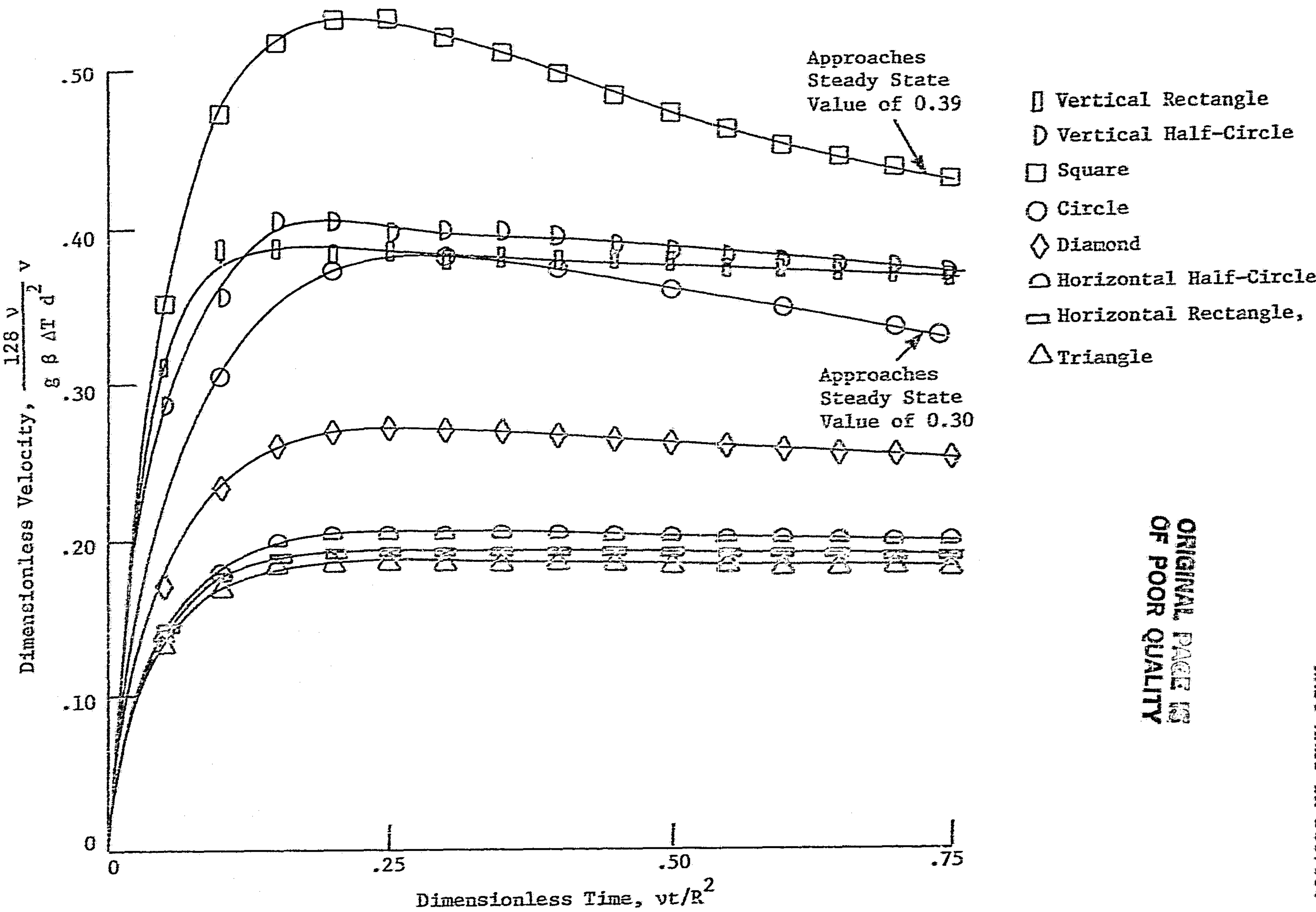

Fig. 7 - Velocity Histories for Natural Convection in Two-Dimensional Enclosures of Various Shape and Rayleigh Number of 5000

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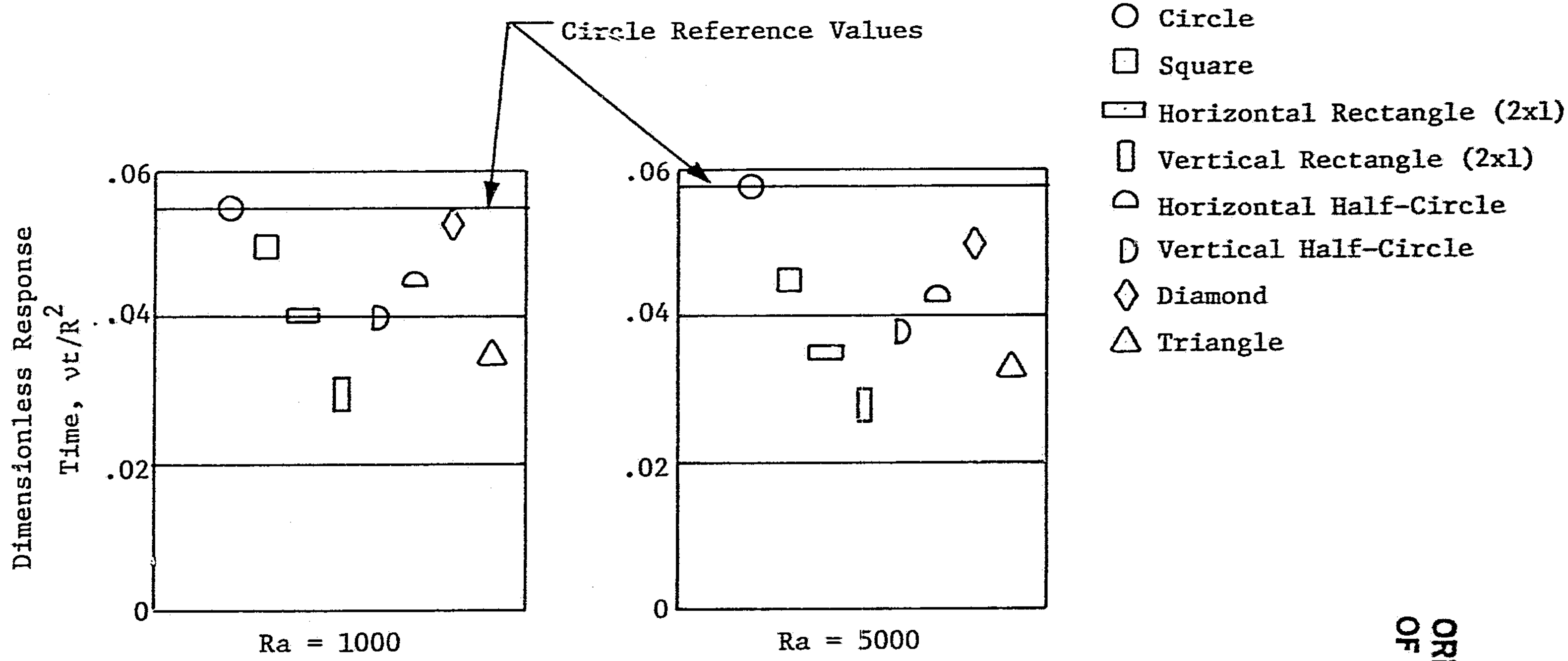

Fig. 8 – Comparison of Response Times for Natural Convection in Two-Dimensional Enclosures of Various Shape

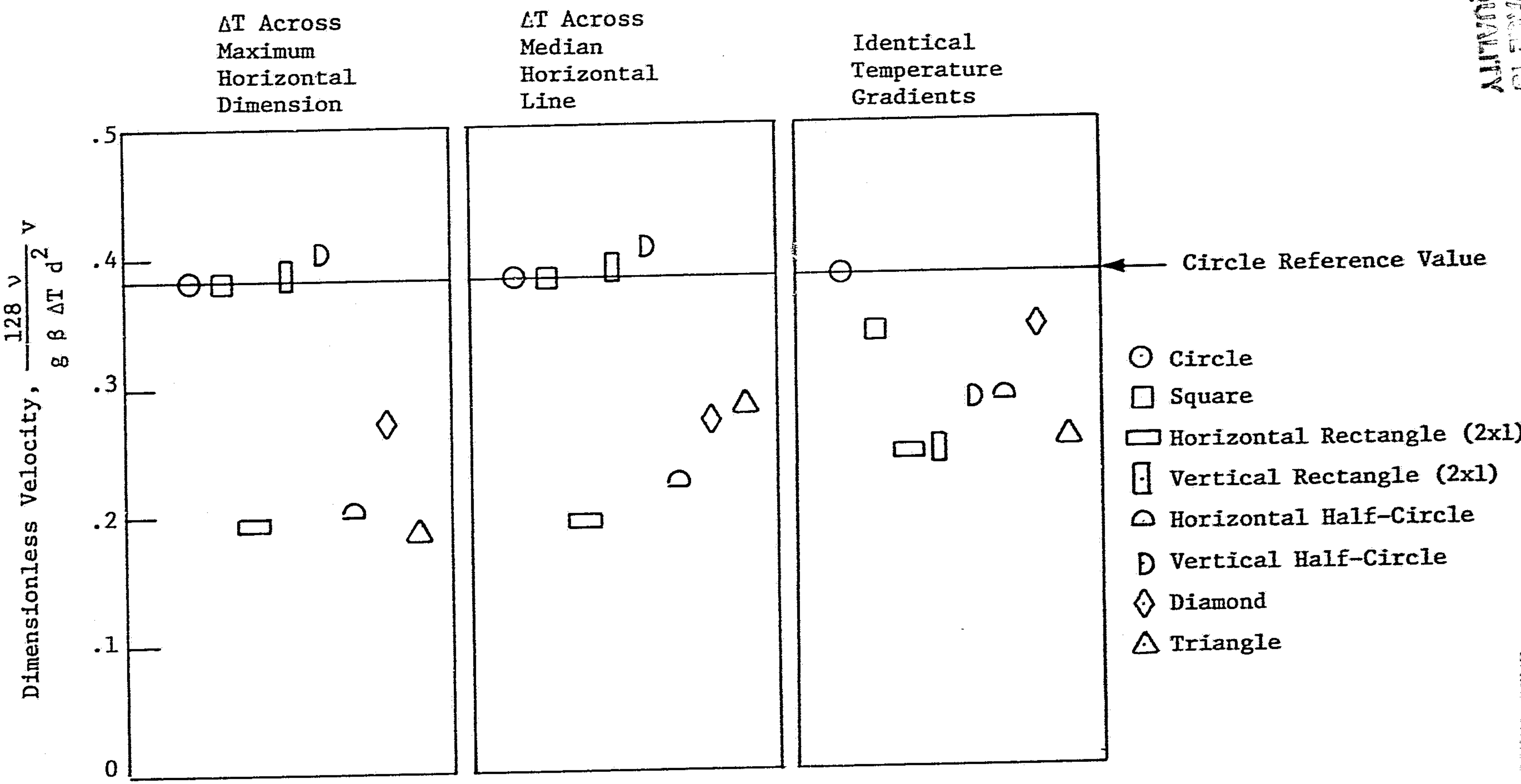

Fig. 9 – Comparison of Steady State Velocities for Natural Convection in Two-Dimensional Enclosures of Various Shape and Rayleigh Number of 1000

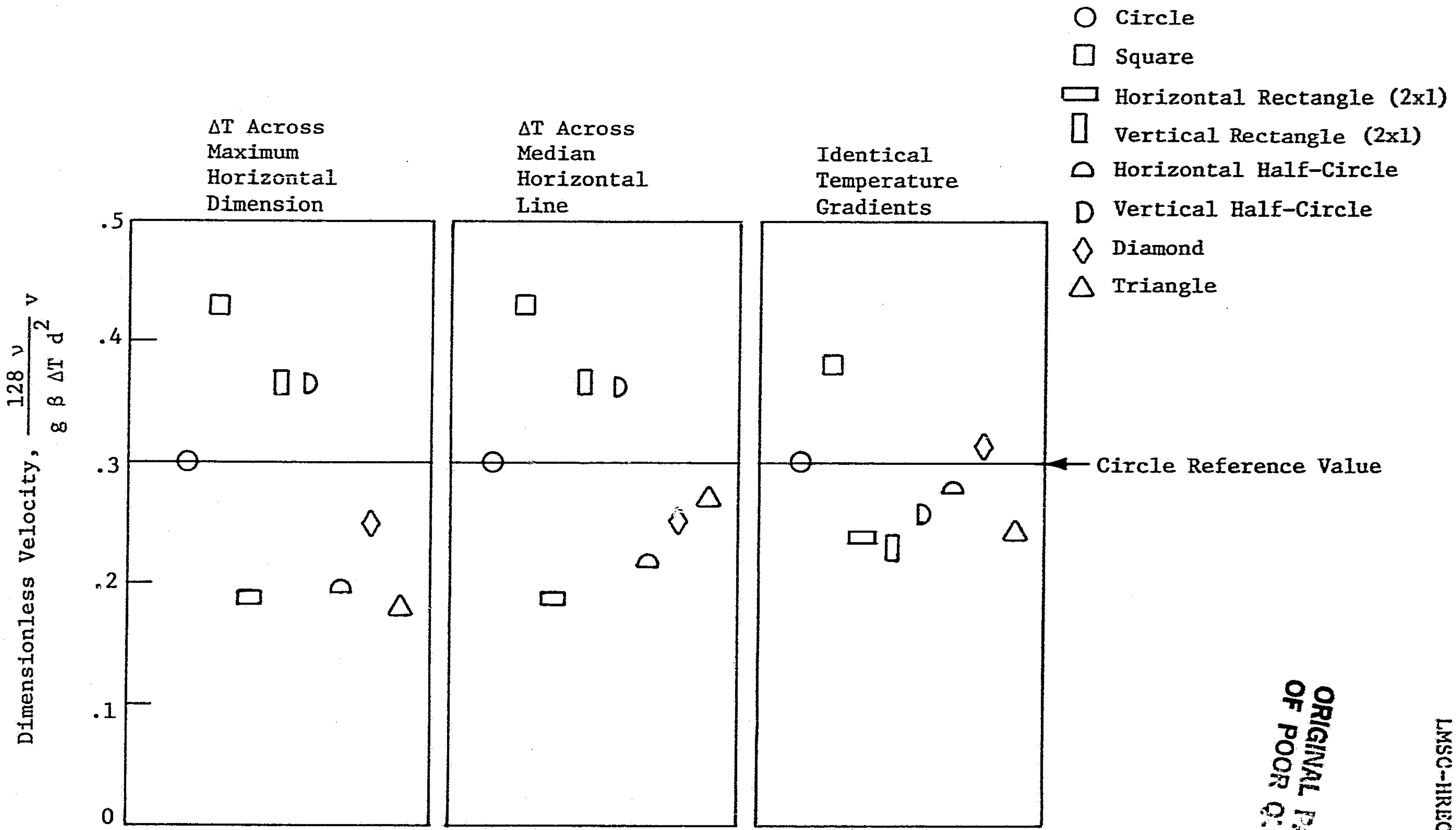

Fig. 10 – Comparison of Steady State Velocities for Natural Convection in Two-Dimensional Enclosures of Various Shape and Rayleigh Number of 5000

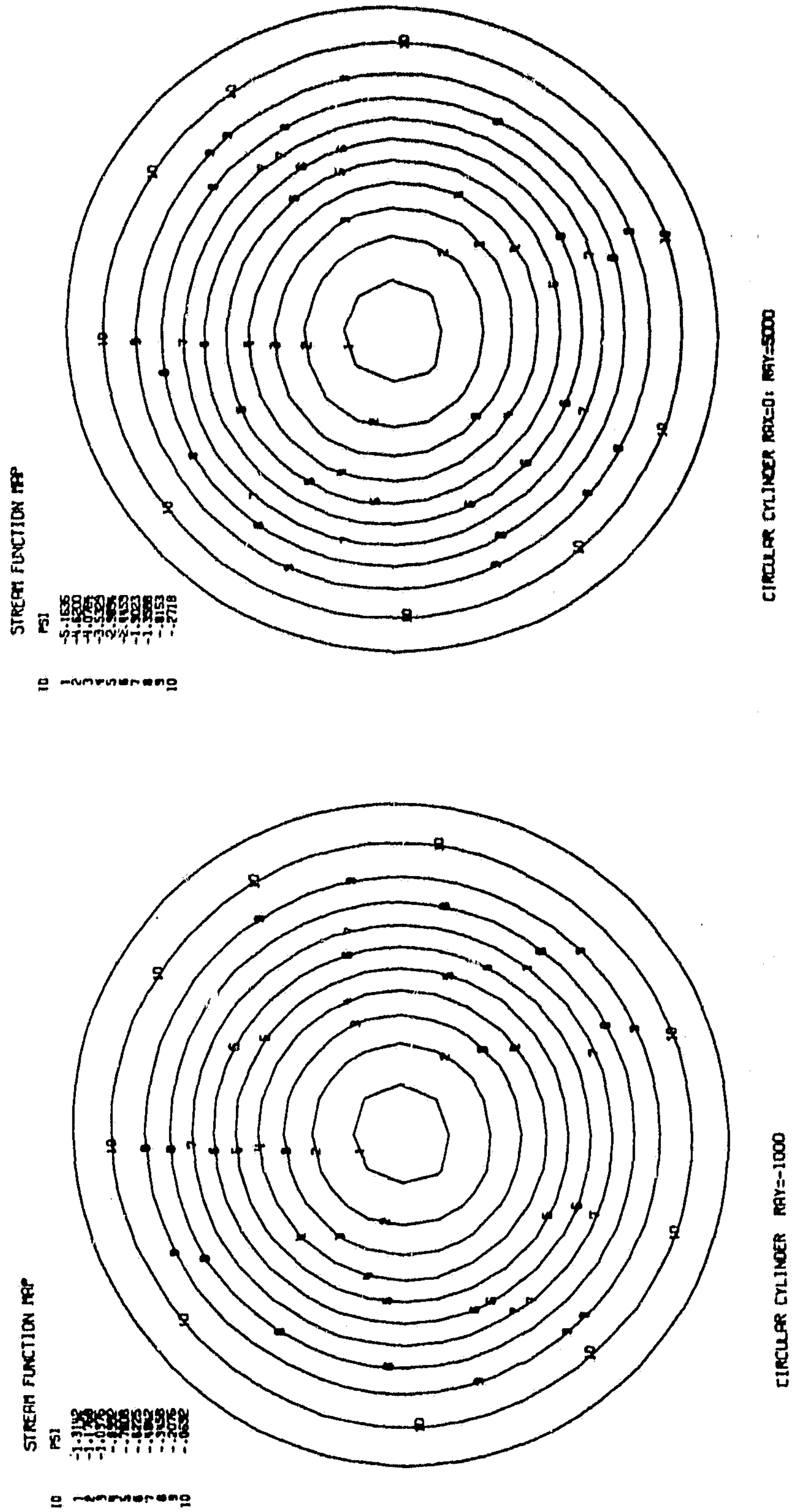

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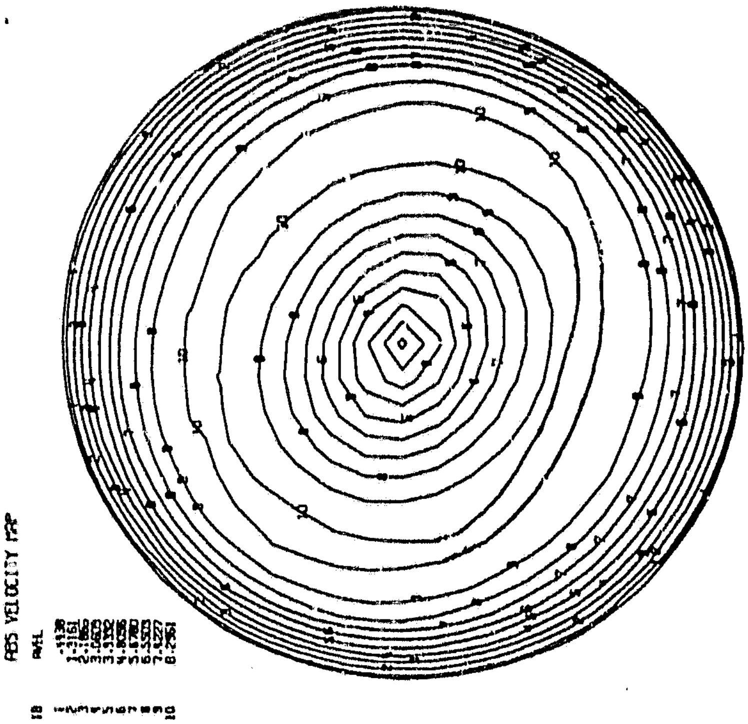
Fig. 11 - Streamline Plots for Circular Enclosure



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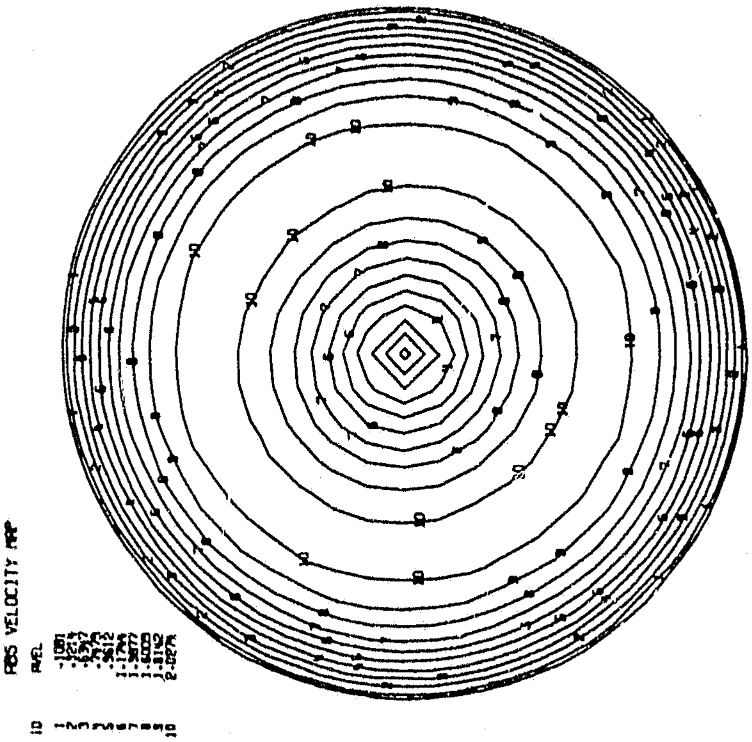

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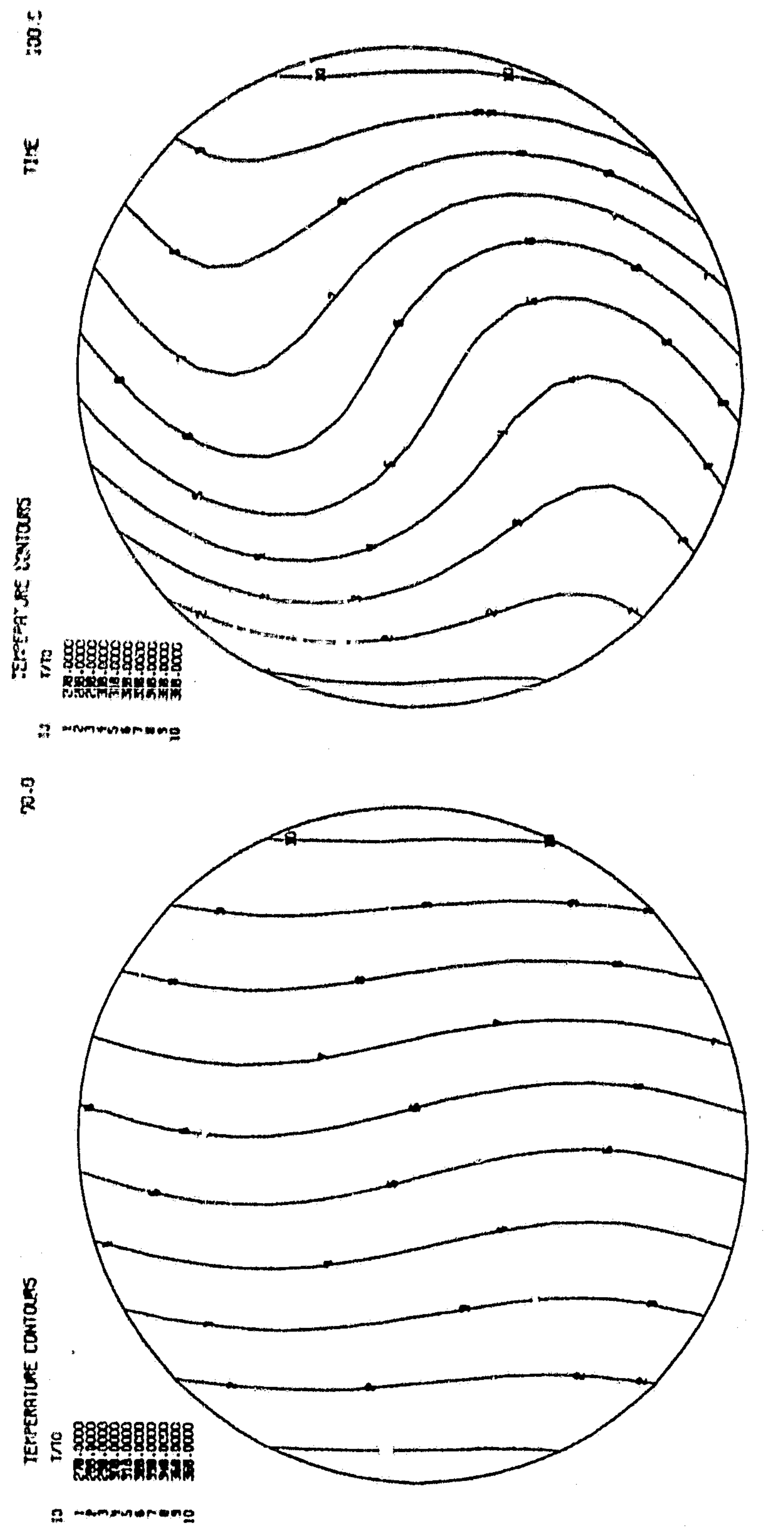
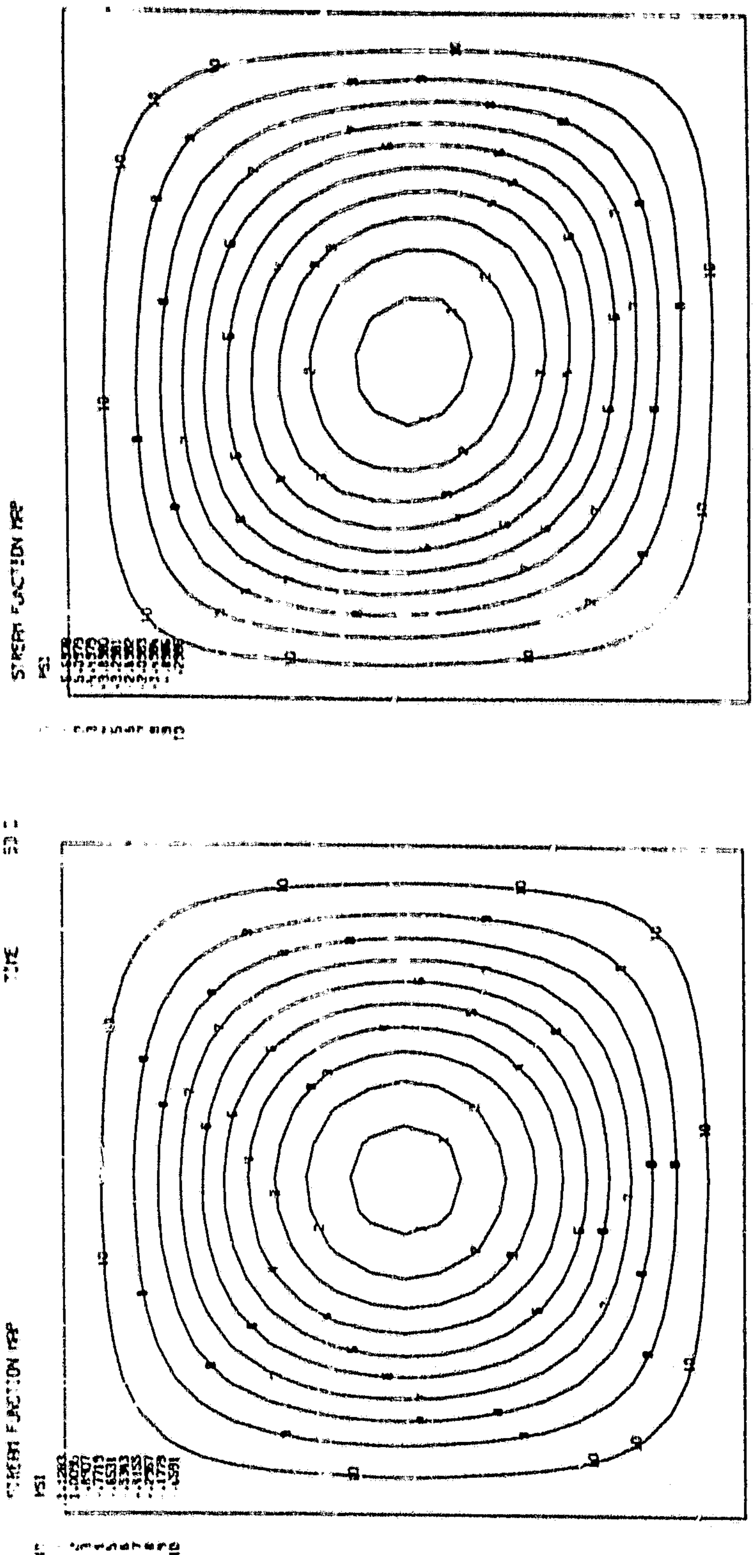
Fig. 12 - Absolute Velocity Contour Plots for Circular Enclosure



Ra = 1000

Ra = 5000

Fig. 13 - Temperature Contour Plots for Circular Enclosure



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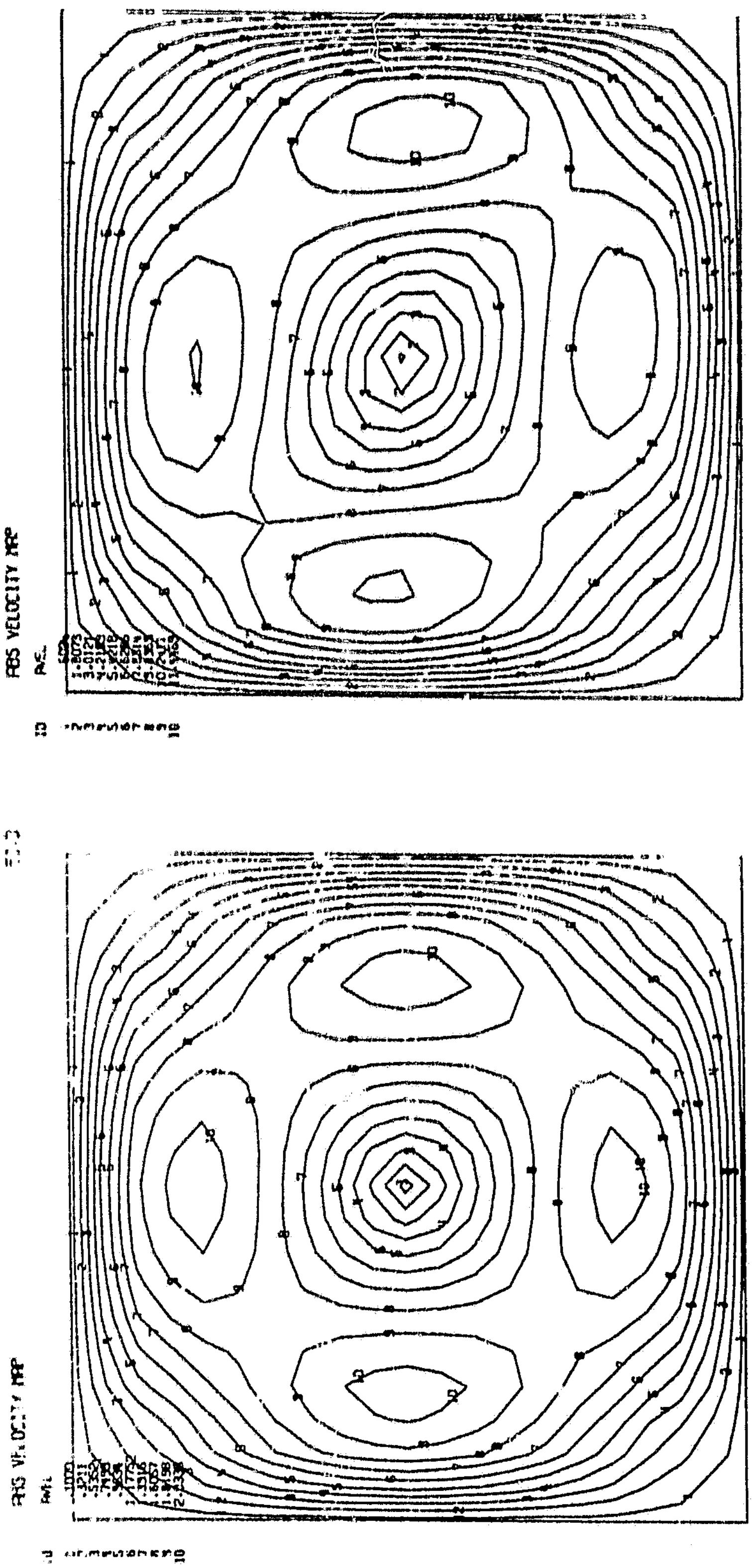
Ra = 1000

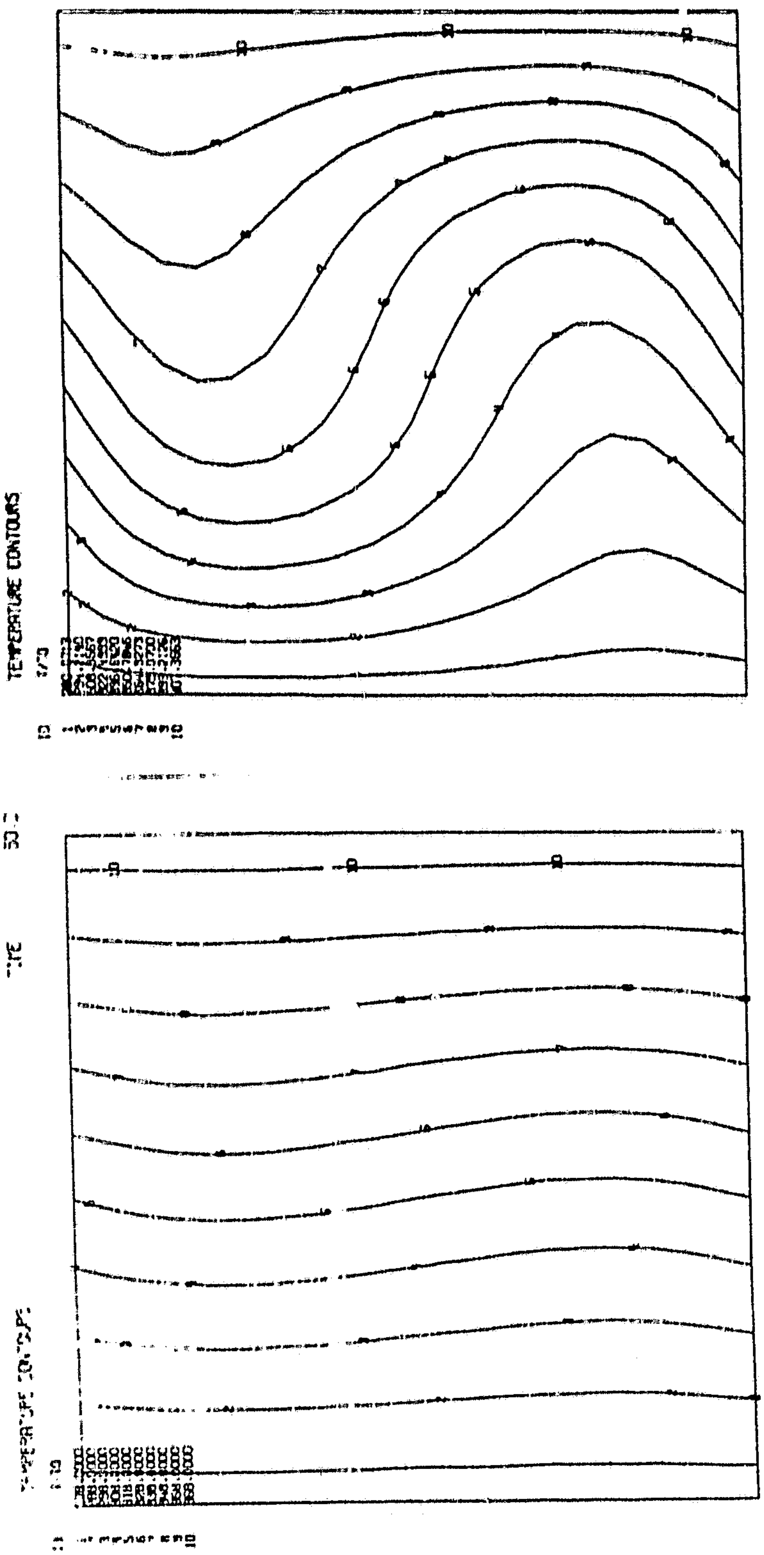
Fig. 14 - Streamline Plots for Square Enclosure



Ra = 5000

Ra = 1000

Fig. 15 - Absolute Velocity Contour Plots for Square Enclosure



Ra = 5000

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Fig. 16 - Temperature Contour Plots for Square Enclosure

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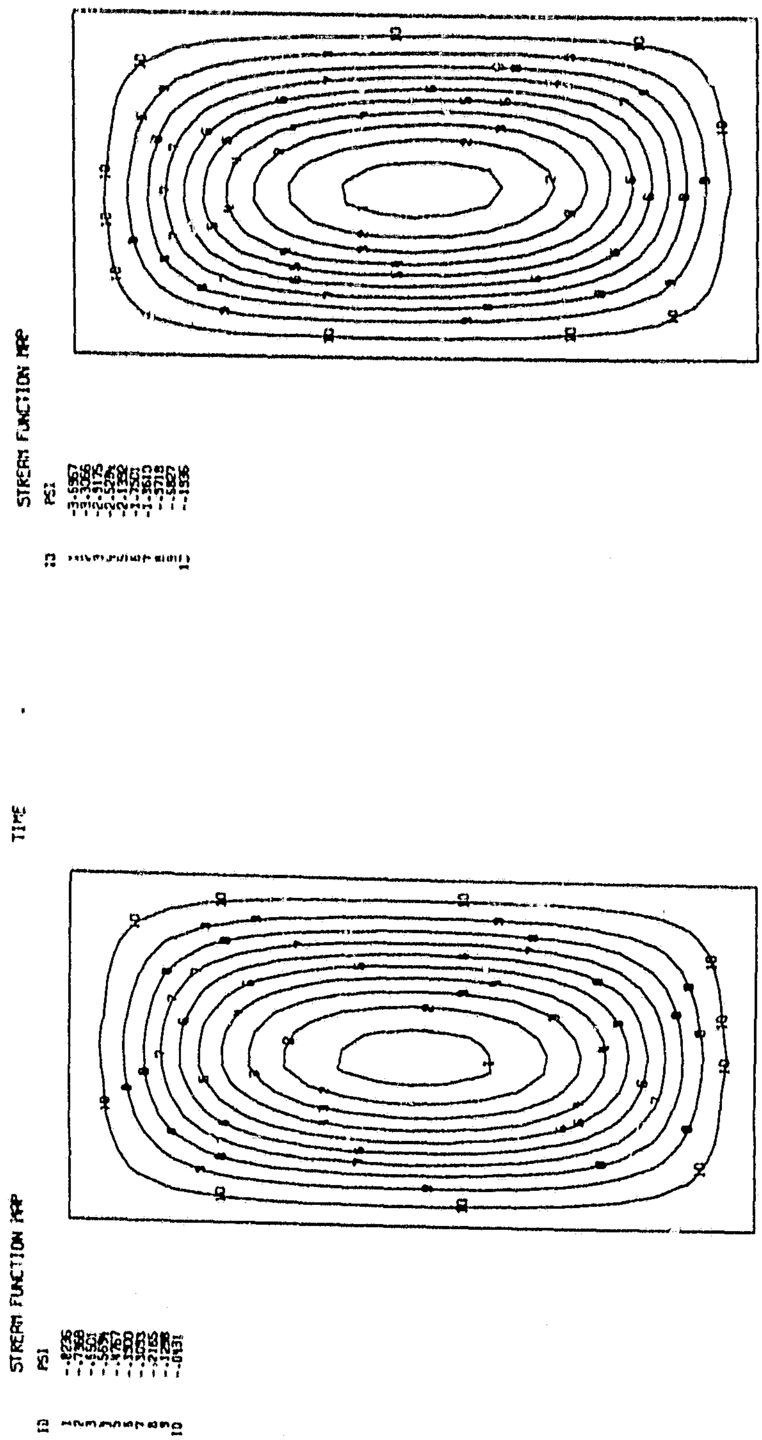

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Fig. 17 - Streamline Plots for Upright 2x1 Aspect Ratio Rectangular Enclosure

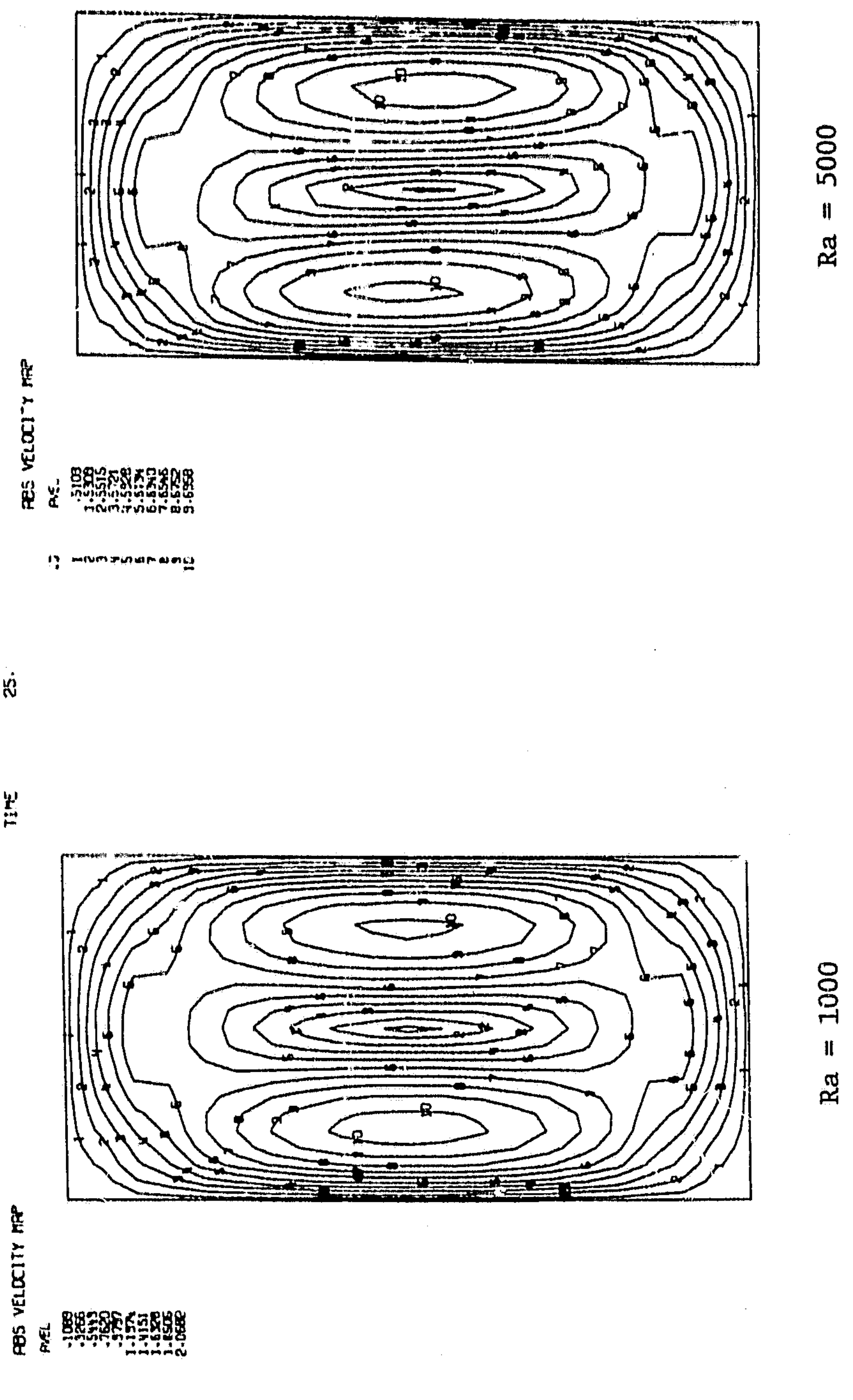
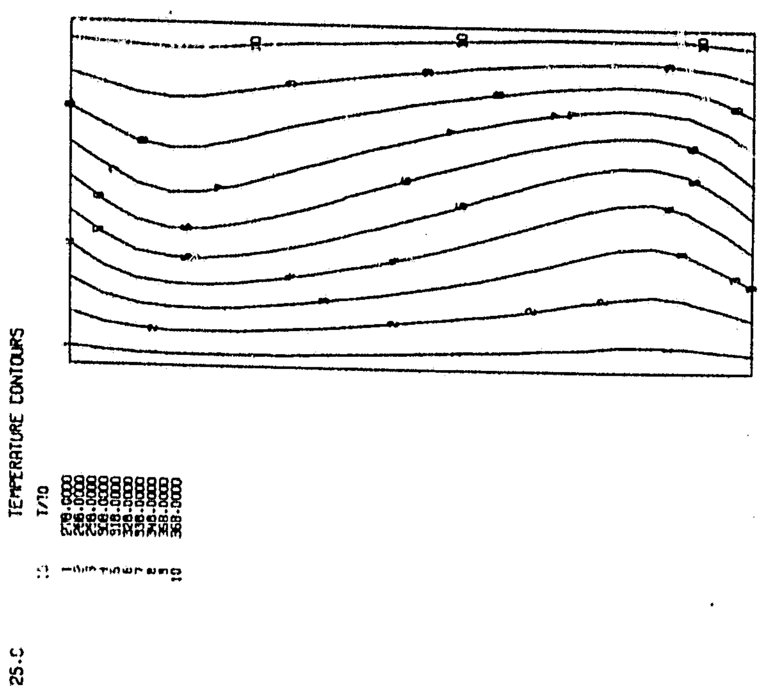


Fig. 18 - Absolute Velocity Contour Plots for Upright 2x1 Aspect Ratio Rectangular Enclosure



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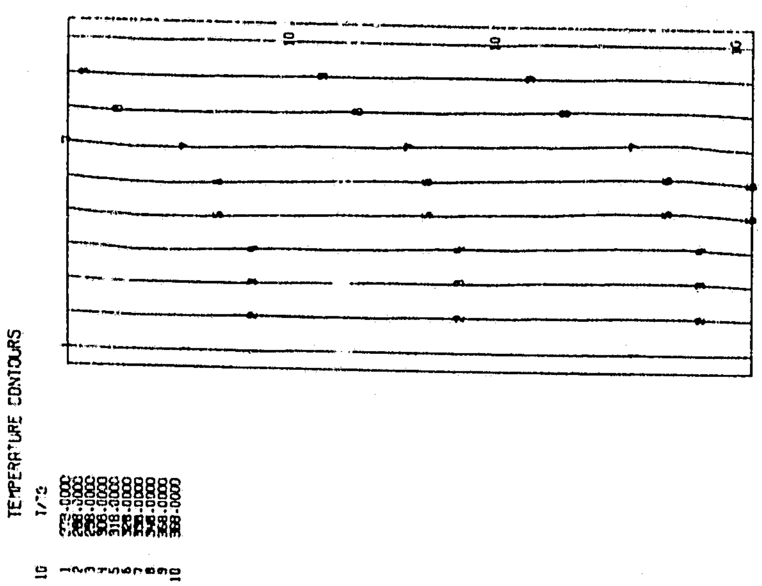

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Fig. 19 - Temperature Contour Plots for Upright 2x1 Aspect Ratio Rectangular Enclosure

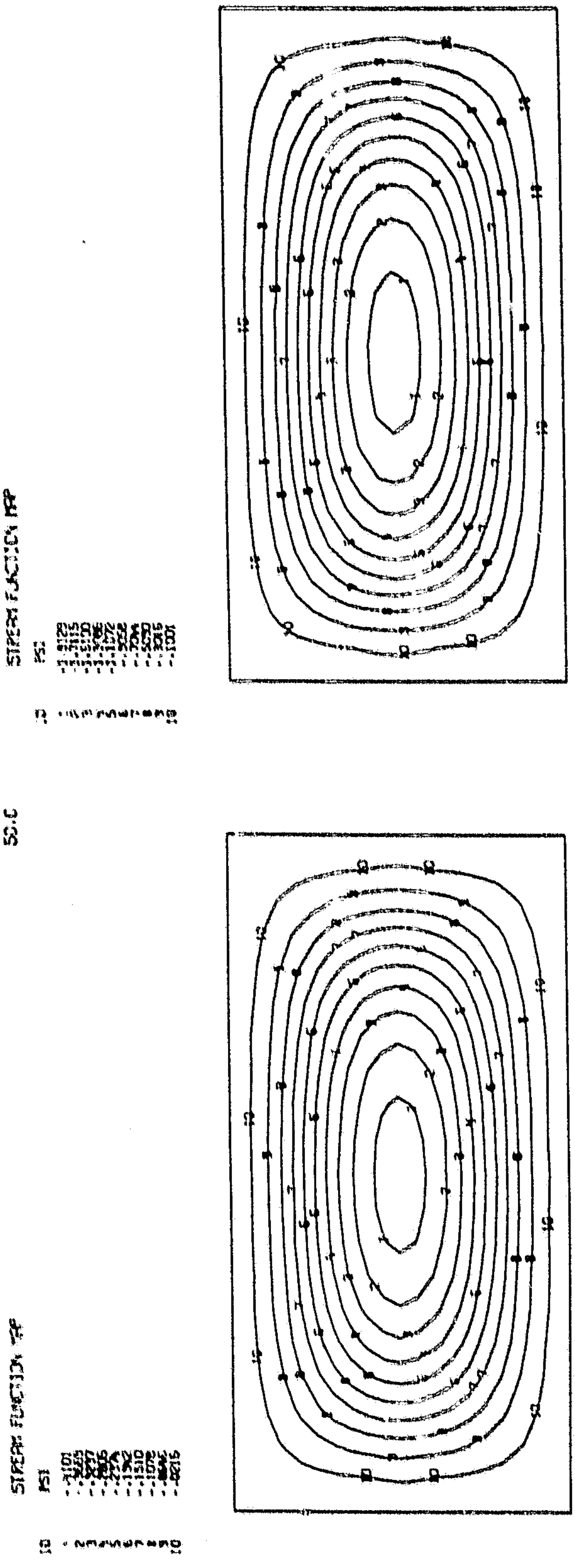

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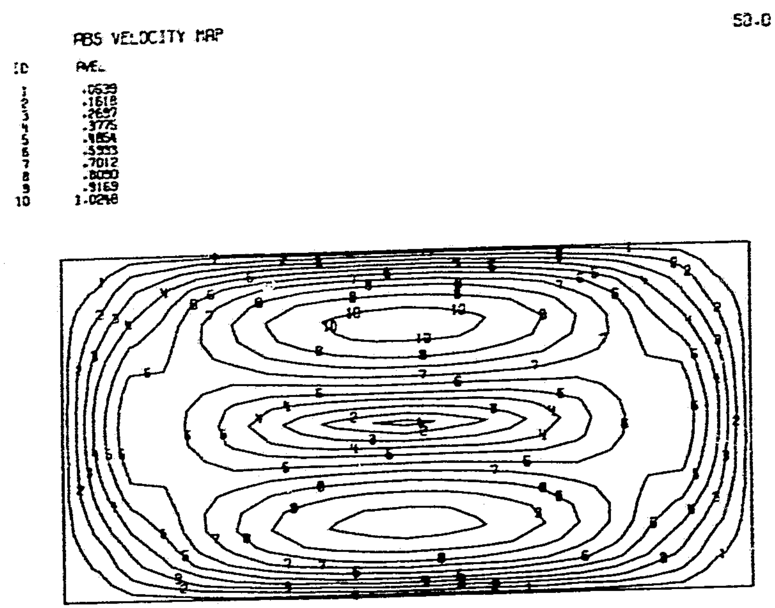
Fig. 20 - Streamline Plots for Horizontal 2x1 Aspect Ratio Rectangular Enclosure



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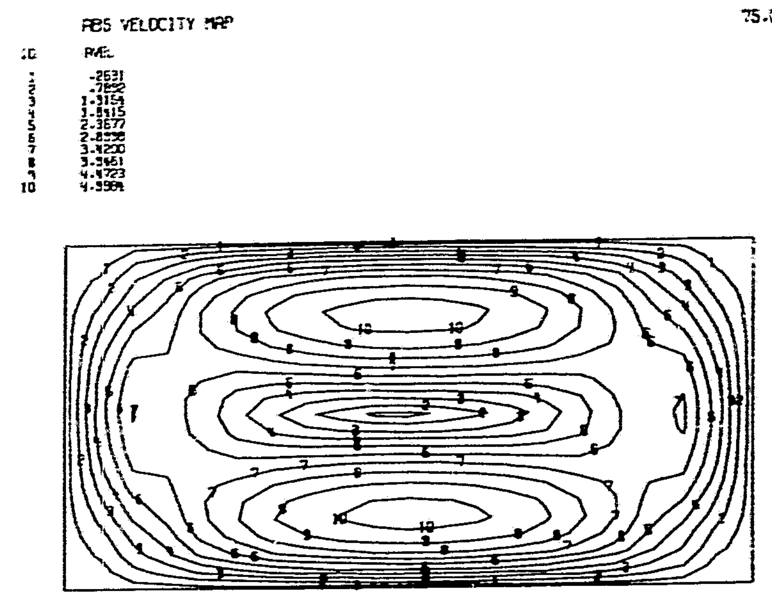

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Fig. 21 – Absolute Velocity Contour Plots for Horizontal 2x1 Aspect Ratio Rectangular Enclosure

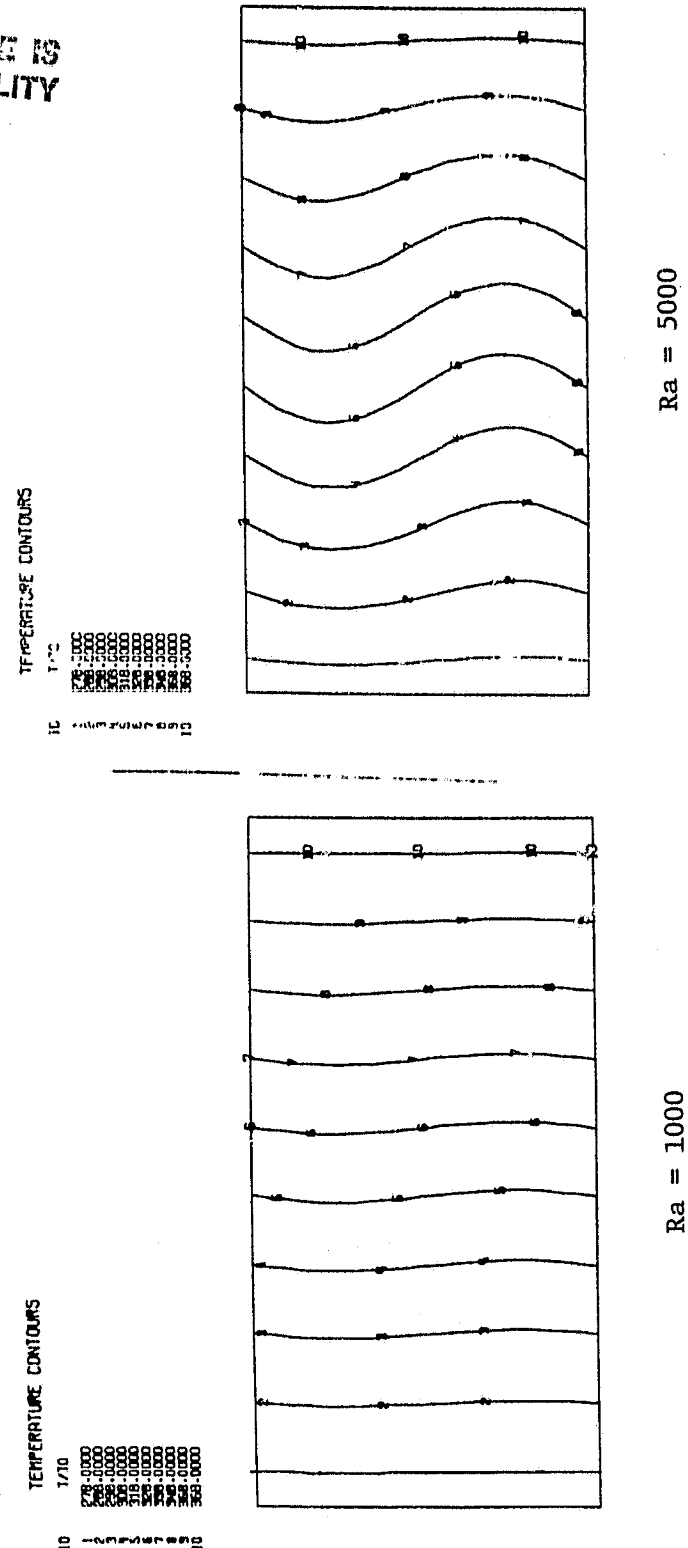

Fig. 22 - Temperature Contour Plots for Horizontal 2x1 Aspect Ratio Rectangular Enclosure

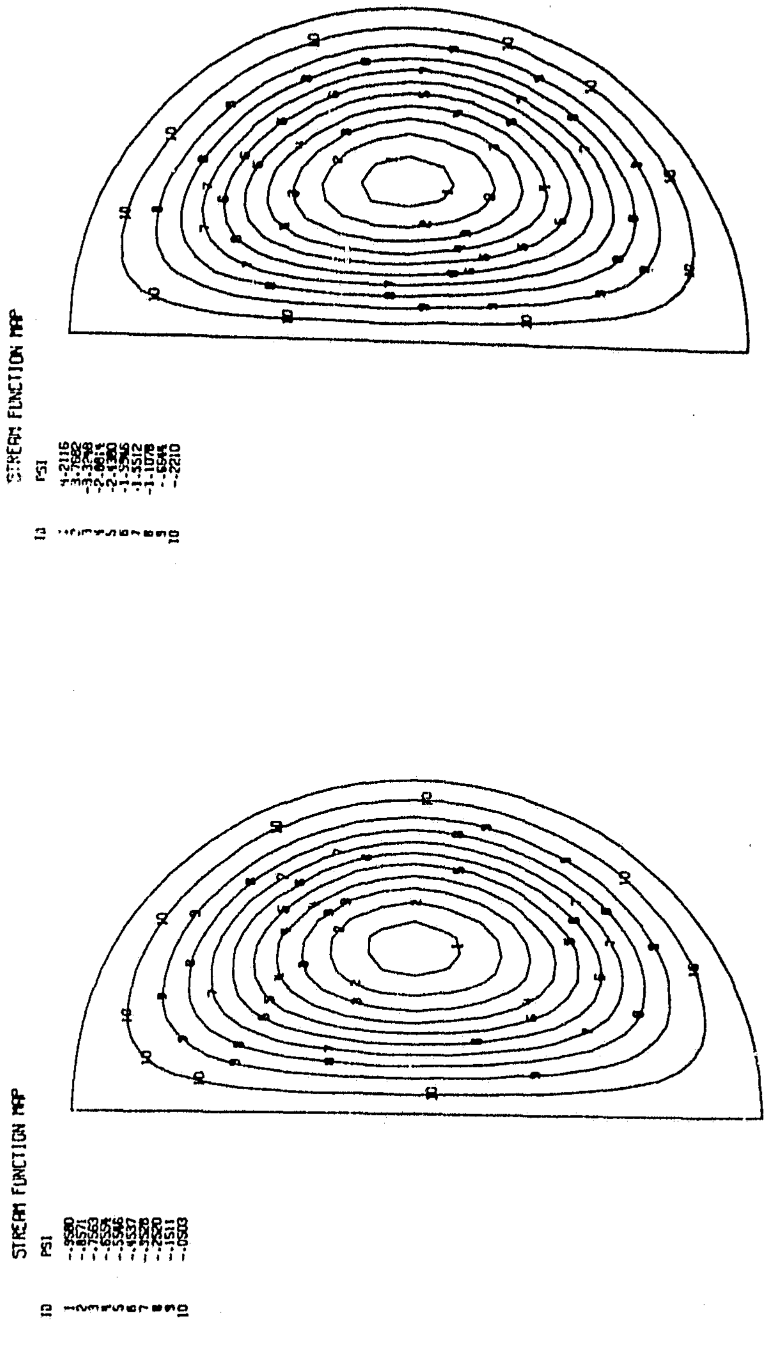

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Fig. 23 - Streamline Plots for Upright Half-Circle Enclosure

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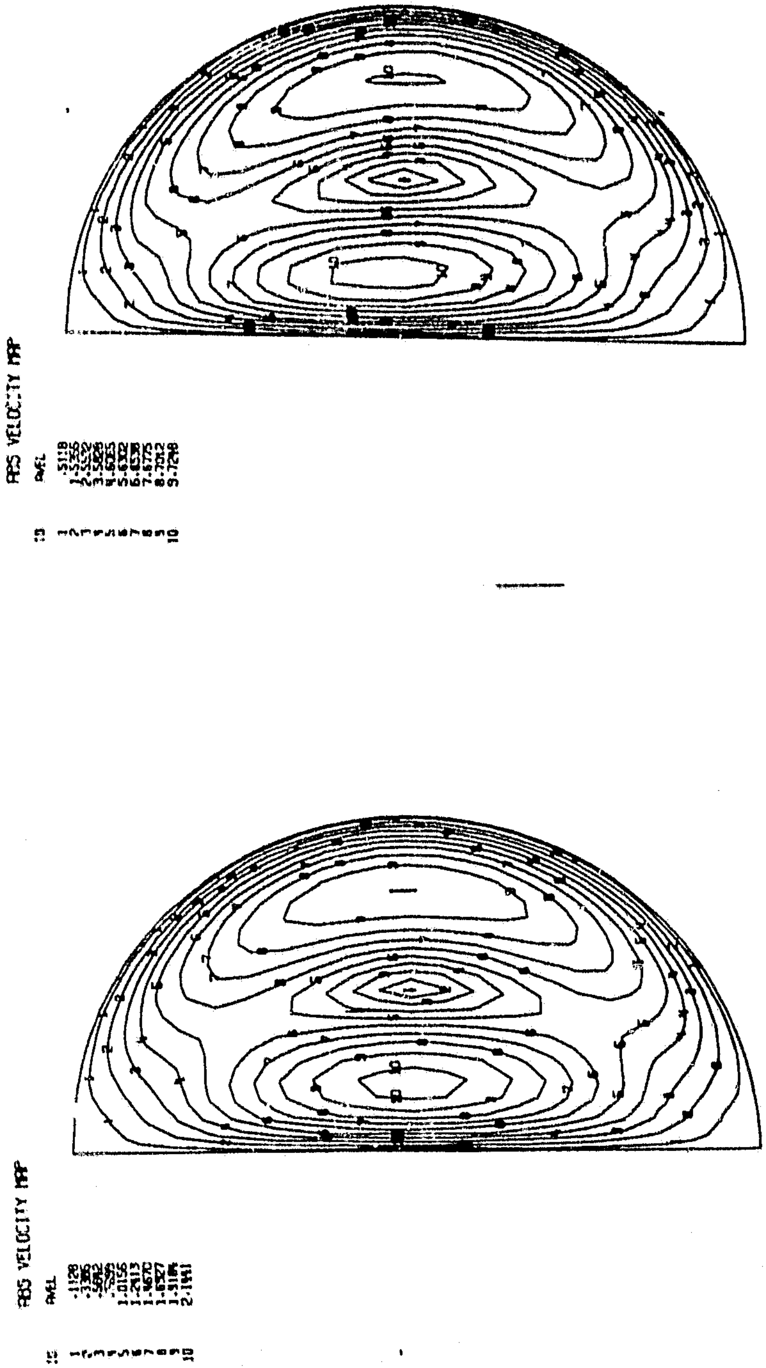

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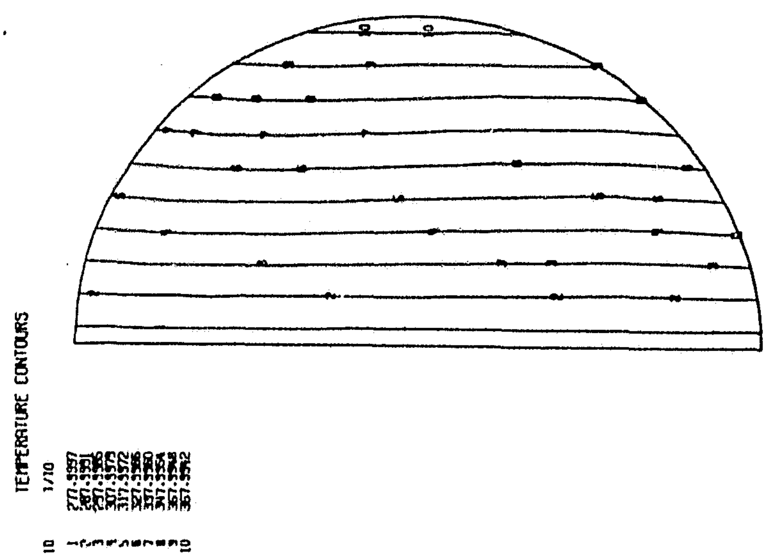
Fig. 24 – Absolute Velocity Contour Plots for Upright Half-Circle Enclosure



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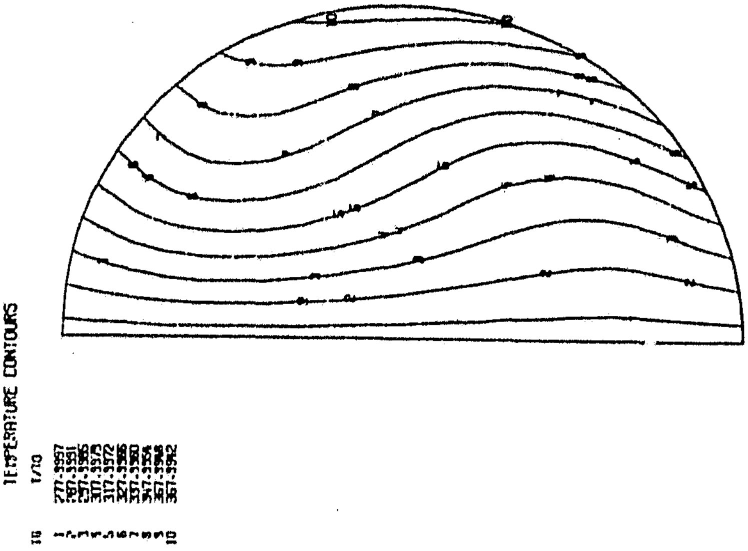

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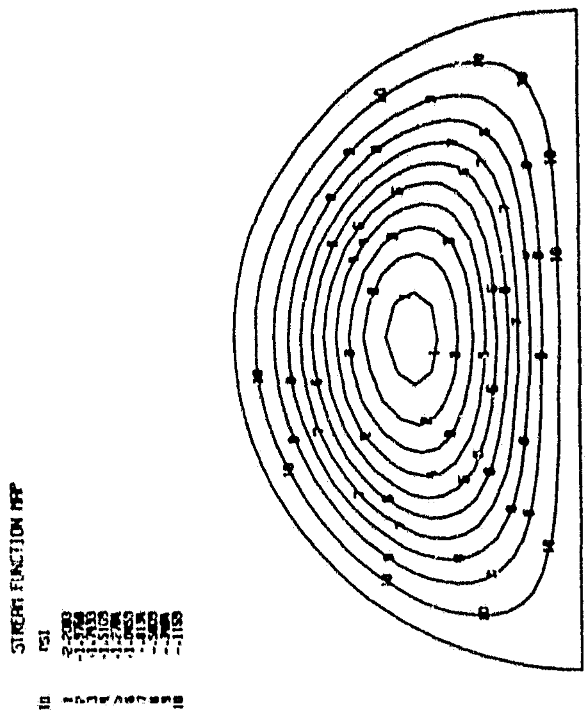
Fig. 25 – Temperature Contour Plots for Upright Half-Circle Enclosure



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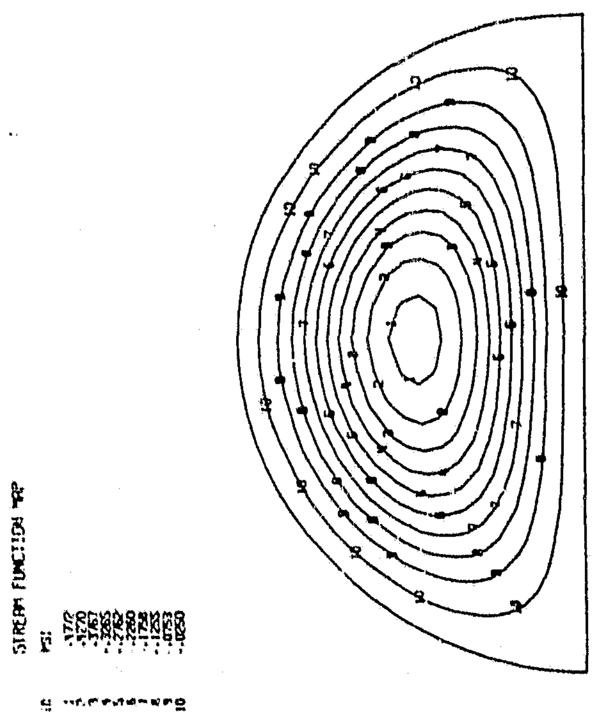

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Fig. 26 - Streamline Plots for Horizontal Half-Circle Enclosure

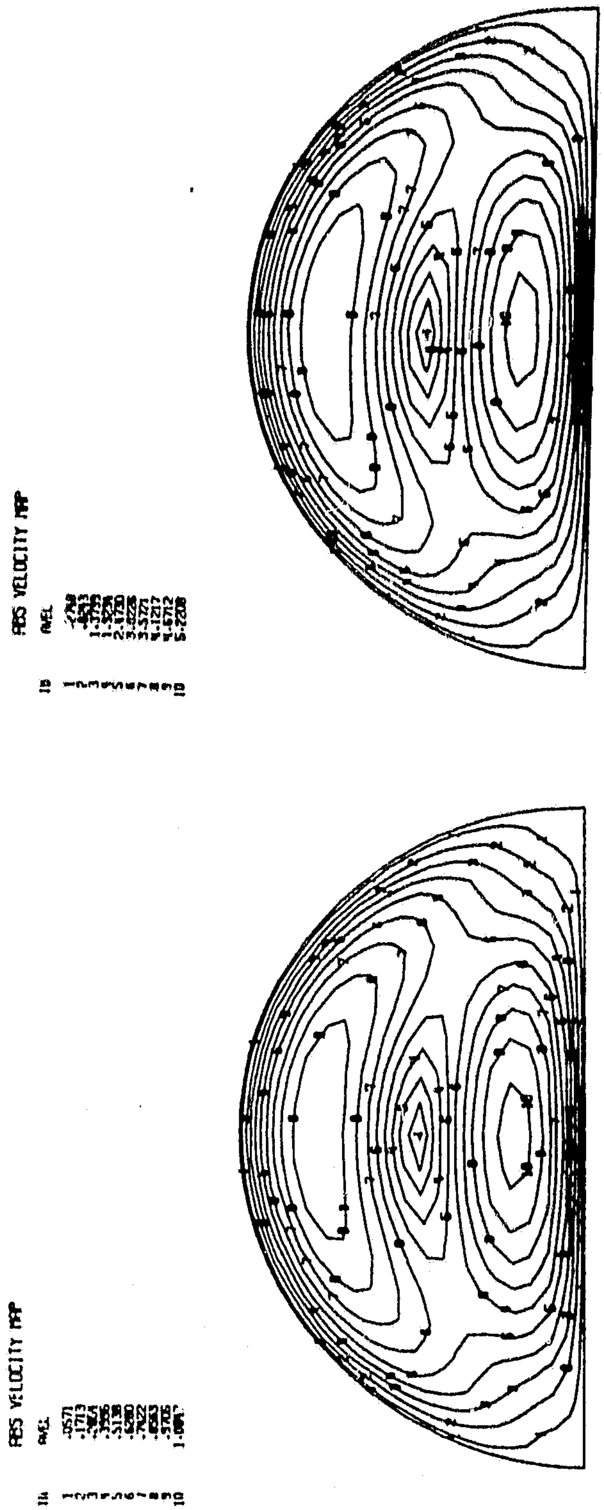

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Fig. 27 - Absolute Velocity Contour Plots for Horizontal Half-Circle Enclosure

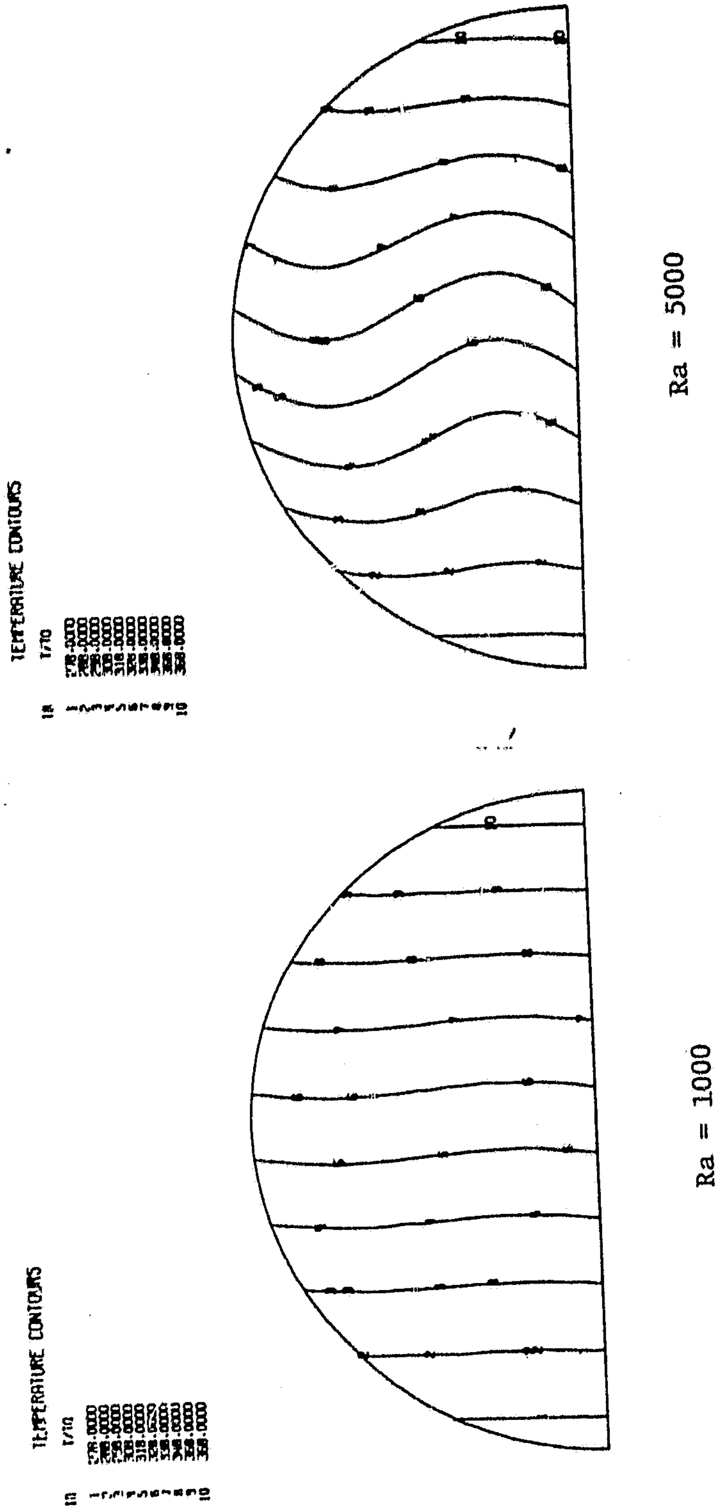

Fig. 28 - Temperature Contour Plots for Horizontal Half-Circle Enclosure

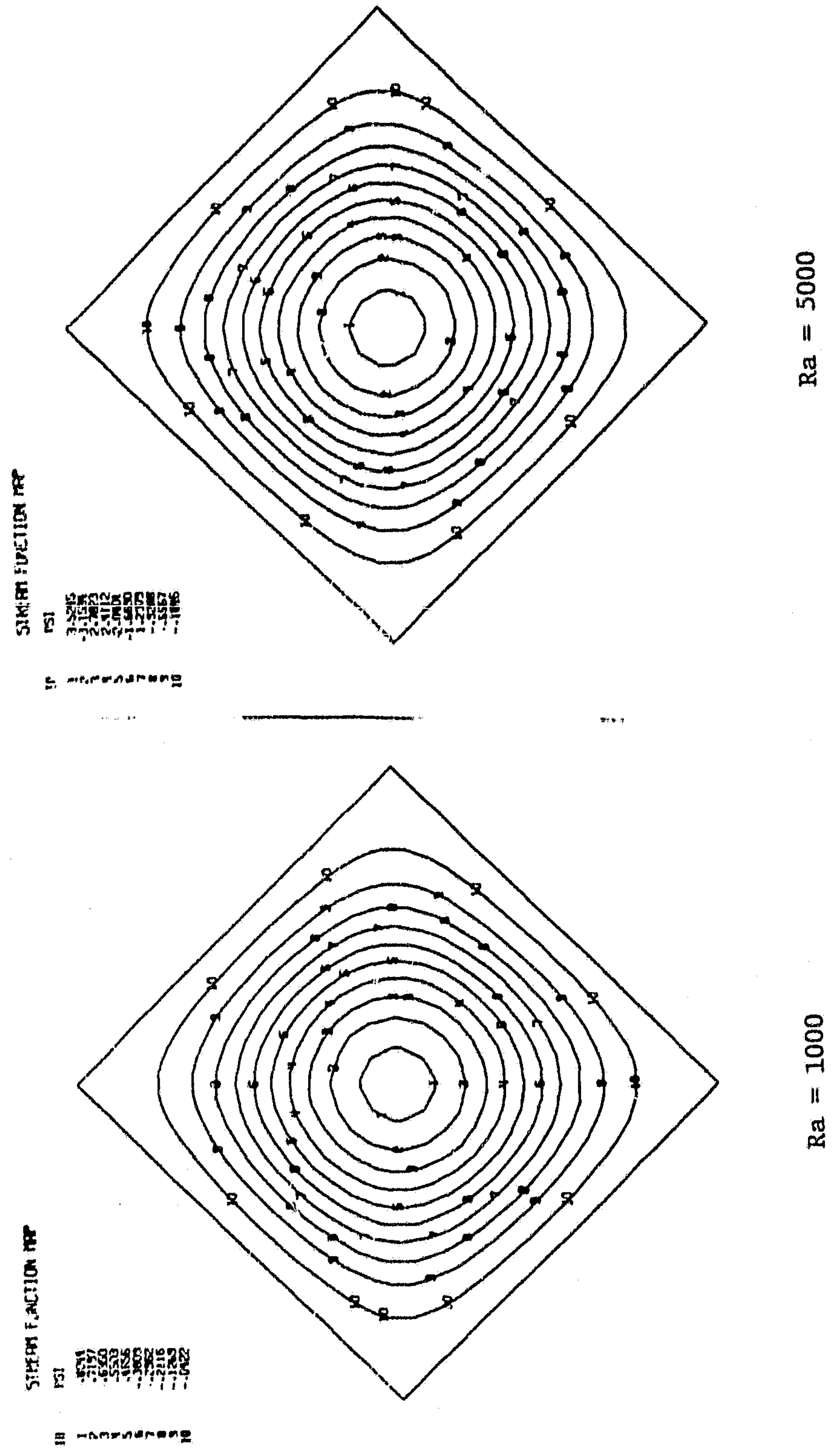

Fig. 29 - Streamline Plots for Diamond Enclosure

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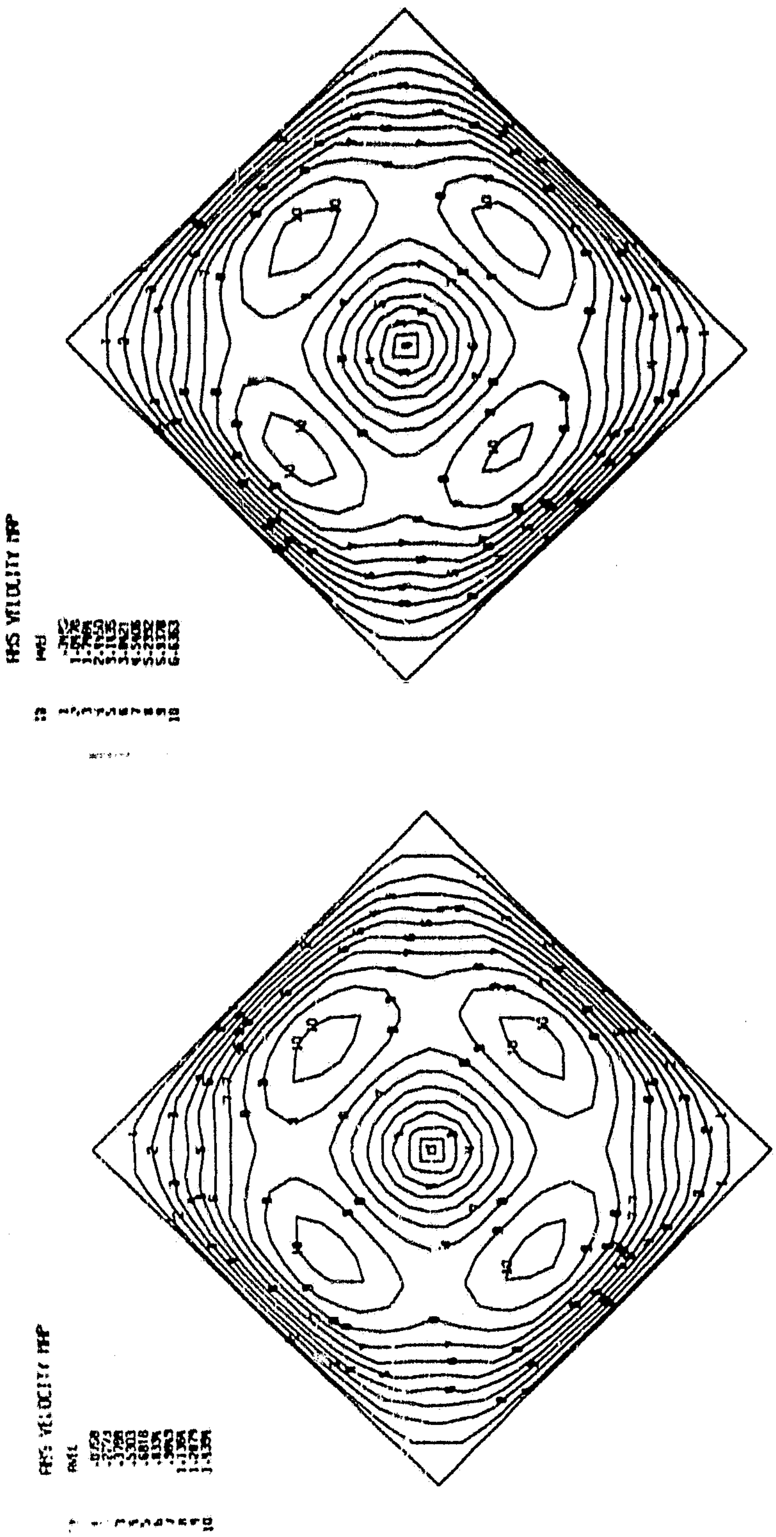

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Fig. 30 - Absolute Velocity Contour Plots for Diamond Enclosure

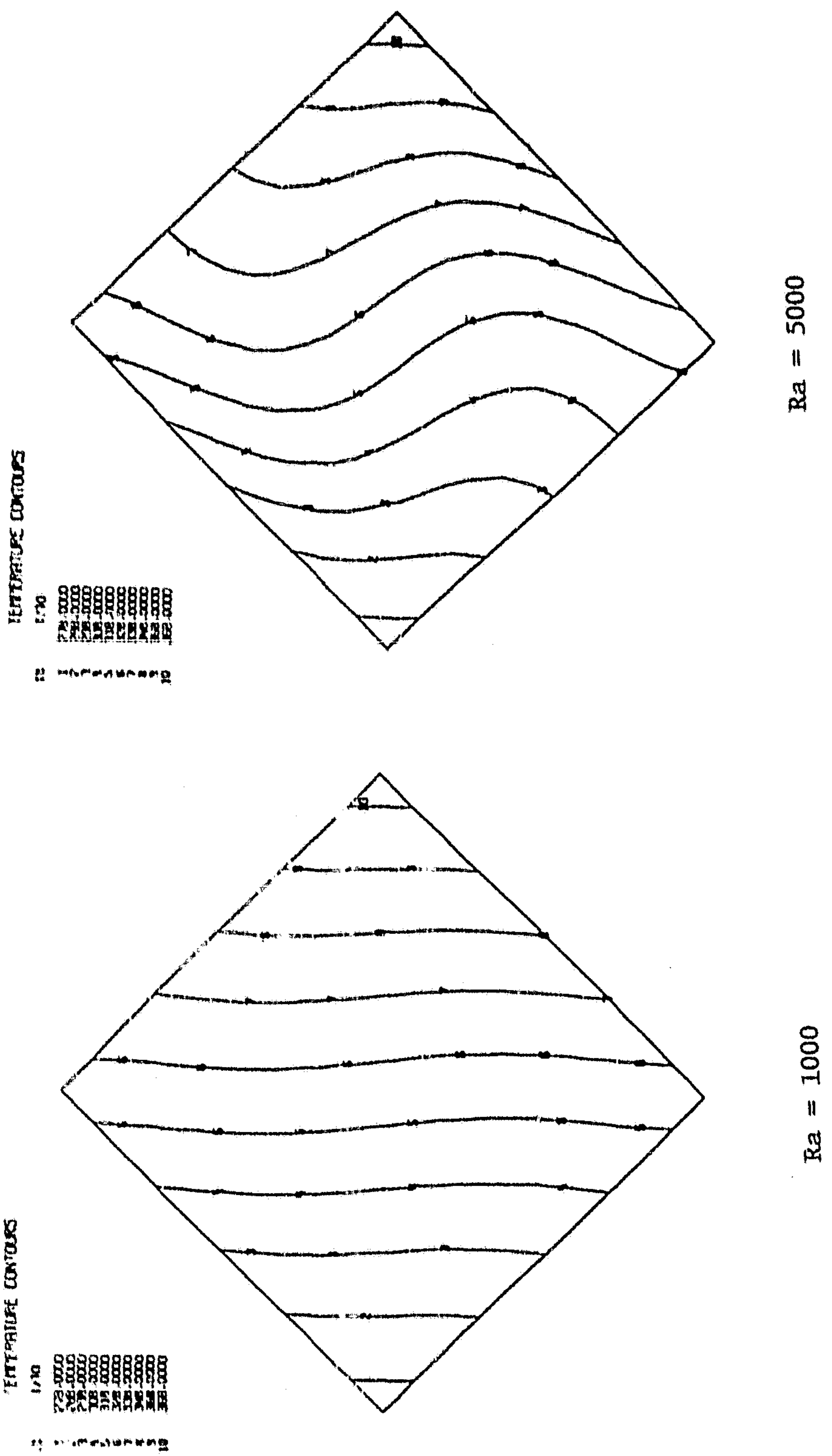

Fig. 31 - Temperature Contour Plots for Diamond Enclosure

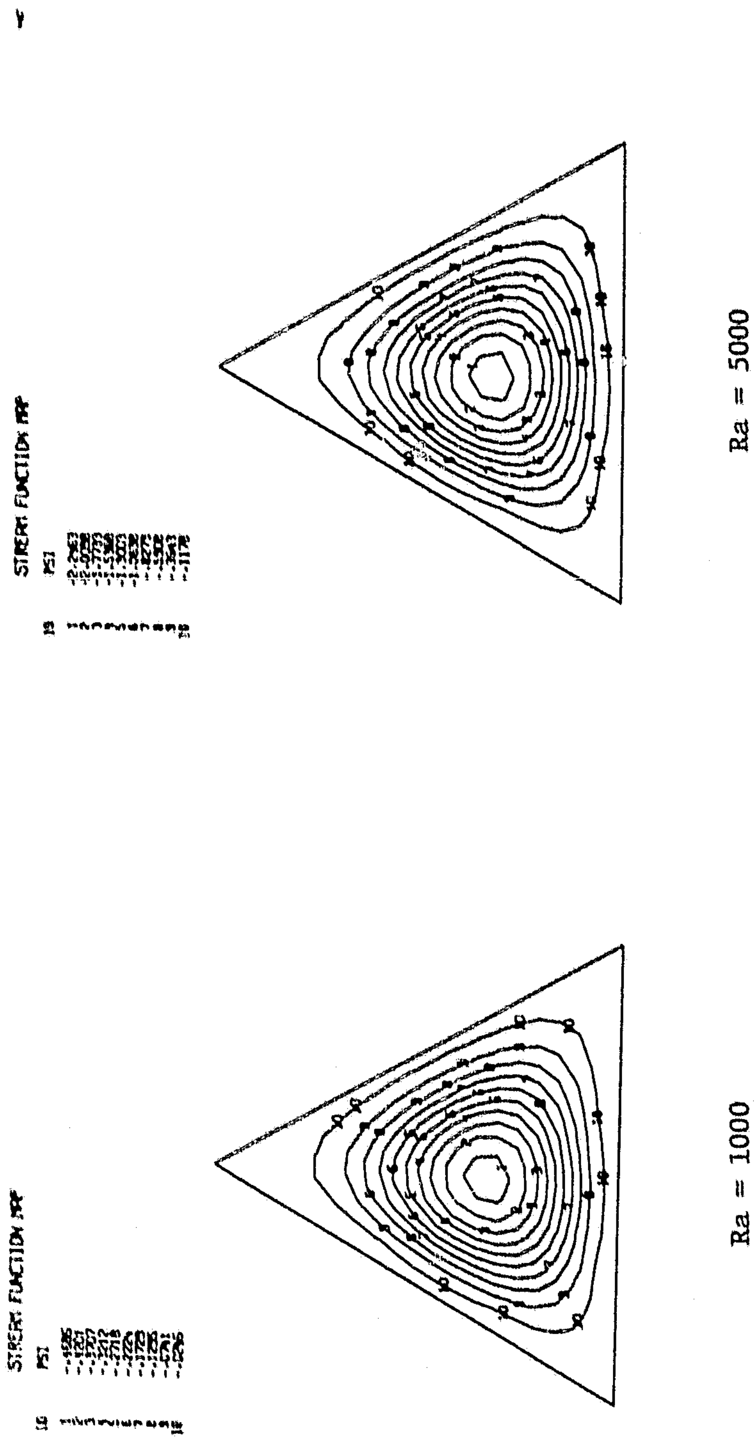

Fig. 32 - Streamline Plots for Triangular Enclosure

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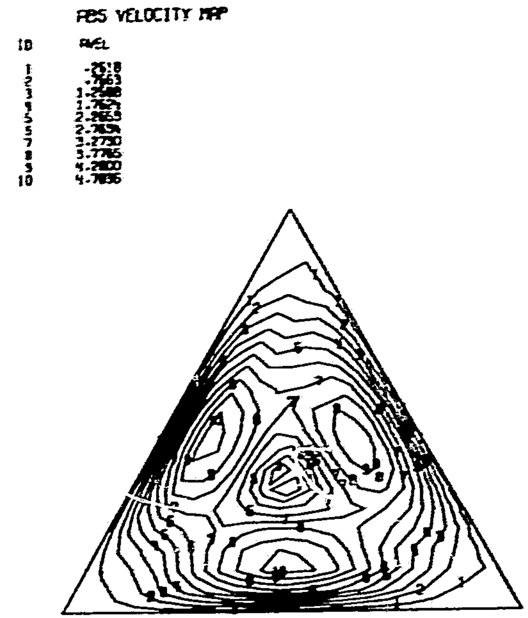

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Fig. 33 - Absolute Velocity Contour Plots for Triangular Enclosure

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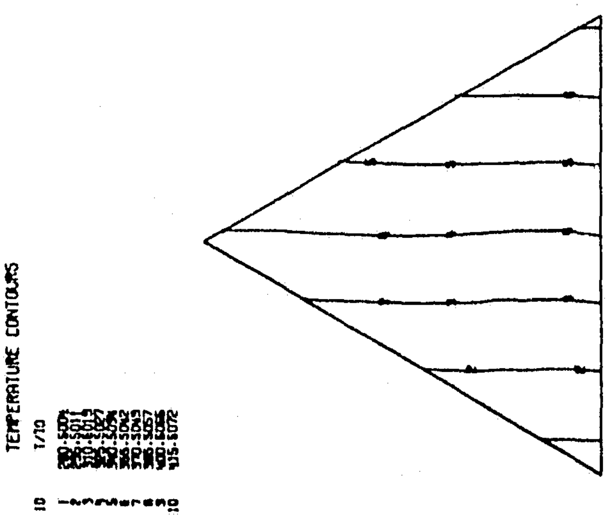

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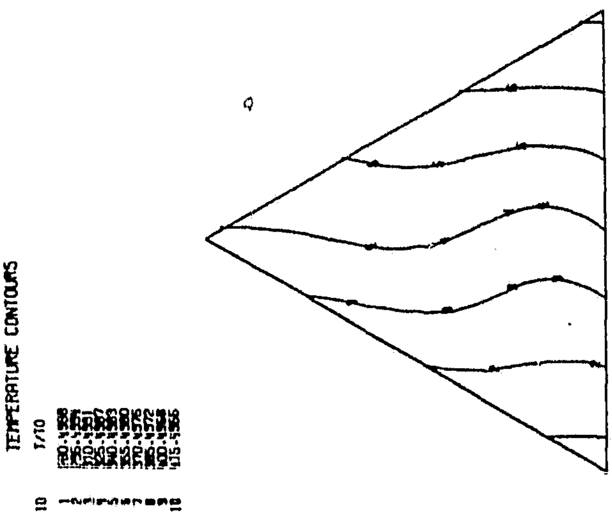

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Fig. 34 - Temperature Contour Plots for Triangular Enclosure